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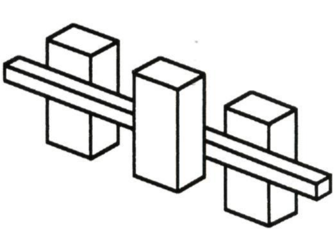
Simplicity of visual shape

A structural information approach



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Robert Jan van Lier

Simplicity of visual shape

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Een wetenschappelijke proeve
op het gebied van de Sociale Wetenschappen

Proefschrift

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Robert Jan van Lier

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Promotor: Prof. Dr. A.J.W.M. Thomassen

Co-promotores: Dr. E.L.J. Leeuwenberg
Dr. Ir. P.A. van der Helm

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Alles ist einfacher, als man denken kann,
zugleich verschränkter, als zu begreifen ist.

J.W. Goethe

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Contents

Preface

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The chapters in this thesis were all written as separate articles, submitted for publication in scientific journals, in inspiriting interaction with Emanuel Leeuwenberg and Peter van der Helm. The various permutations of our names in Chapters 1 to 6 witness to that cooperation.

The conception of separate articles has the advantage that each chapter can be read independently from the other chapters. A disadvantage might be that there is some overlap in the articles. We trust, however, that some redundancy does not reduce the readability of this thesis.

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Van der Helm P, Van Lier R, Leeuwenberg E, 1992 "Serial pattern complexity: irregularity and hierarchy" Perception **21** 517-544

Chapter 2 has been published as

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Chapter 3 has been published as

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16th European Conference on Visual Perception, 25-29 August 1993, Edinburgh, United Kingdom. Van Lier R, Van der Helm P, Leeuwenberg E, 1993 "Global and local completions in visual occlusion" *Perception*, **22**, 49-50 (suppl.)

Annual meeting of the Association for Research in Vision and Ophthalmology (ARVO), 1-6 May 1994, Sarasota, Florida (USA). Van Lier R, Van der Helm P, Leeuwenberg E, 1994 "Multiple completions in visual occlusion" *Investigative Ophthalmology & Visual Science*, **35** (suppl.), 1665

The Trieste Symposium on Cognition and Perception, 13-15 October 1994, Trieste, Italy. Van Lier R, Leeuwenberg E, Van der Helm P "Perceived completions are not alone"

Workshop on Structural Information Theory, 6-9 December 1994, Leipzig, Germany. Van Lier R "Global and local aspects in visual occlusion"

Symposium on phenomena and architectures of cognitive dynamics, 29 June - 1 July 1995 Leipzig, Germany. Van Lier R, Leeuwenberg E, Van der Helm P "In support of structural hierarchy in visual shape"

INTRODUCTION AND OVERVIEW

1 Introduction

Simplicity of visual shape refers to a quality of perception. Given the assumption that "visual shape" alludes to the internal representation of a distal stimulus, the "simplicity of visual shape" comprises an overall property of such an internal representation. This notion of simplicity is a central issue within the *Structural Information Theory* (SIT), initiated by Leeuwenberg (1969, 1971). This theory has been applied quite successfully to a broad range of phenomena, such as judged complexity (Leeuwenberg, 1971), perceptual ambiguity (Buffart, Leeuwenberg, & Restle, 1983), figural completion (Buffart, Leeuwenberg, & Restle, 1981), figure-ground organization (Leeuwenberg & Buffart, 1984), beauty (Boselie & Leeuwenberg, 1985), assimilation and contrast (Leeuwenberg & Buffart, 1982), brightness illusions (Van Tuyl, 1975; Van Tuyl & Leeuwenberg, 1979, 1982), judged temporal order (Collard & Leeuwenberg, 1981), sequence influence (Van Leeuwen, Buffart, & Van der Vegt, 1988), and concurrent presence (Mens & Leeuwenberg, 1988).

In perception research, the notion of simplicity goes back to the early *Gestalt* psychologists (e.g. Wertheimer, 1912; Köhler, 1920; Koffka, 1935). In order to predict perceived interpretations of visual patterns, these psychologists formulated various so-called Gestalt laws, such as good continuation, closure, and proximity. It appeared, however, to be virtually impossible to predict which rule applies to what pattern. Moreover, there was no a-priori hierarchy between the separate laws: in principle, each law could overrule - or could be overruled by - another law. In order to cope with these problems, Koffka (1935) formulated the law of *Prägnanz*. This law can be regarded as an attempt to integrate the Gestalt laws, and stresses an overall tendency towards "good" forms. Nevertheless, even on the basis of this general law, predictions of perceived interpretations could hardly be made, as no clear specifications about the goodness of form were given. An important step forward was the formulation of the *global-minimum principle* by Hochberg and McAlister (1953). The global-minimum principle states that for a given pattern its simplest possible interpretation will be perceived. Hatfield and Epstein (1985) made a distinction between three types of simplicity: procedural simplicity, phenomenal simplicity, and descriptive simplicity. Procedural simplicity requires that the preferred interpretation is attained by the most economical process. The notion of phenomenal simplicity endorses the idea that the preferred interpretation contains a maximum of regularity. Finally, the notion of descriptive simplicity states that the description of the preferred interpretation is as compact as possible. The above notions do not exclude each other. Actually, the latter two are more or less integrated in the claim within SIT that the simplest description reflects the interpretation with the highest degree of regularity. To be clear, the global-minimum principle as conceived within SIT is not assumed to deal with the process of perception, but with the *outcome* of that process.

Hatfield and Epstein (1985) further remarked that the global-minimum principle is an empty concept if it does not have an operationalization, that is, it needs a measure of simplicity. Indeed, in order to test the global-minimum principle, a quantifiable measure of simplicity is required (cf. Boselie & Leeuwenberg, 1986). To that end, a perceptual *coding system* and a measure of simplicity have been developed within SIT (Leeuwenberg, 1969, 1971; Van der Helm & Leeuwenberg, 1991). By means of that coding system *regularities* in the pattern are accounted for. The simplicity of a code depends on the number of descriptive components in a code, and is expressed in terms of *structural information*. In general, the degree of regularity in a pattern and the number of descriptive components in the code are inversely related. At several instances in this thesis more attention will be paid to the coding system that is employed within SIT.

2 Some anti-SIT arguments and some alternative approaches

The alleged tendency towards simplicity in visual perception is not without controversy: various objections against SIT and the minimum principle have been made during the past years. Some of them concern the coding system, others are related to certain phenomena of perceptual organization. In the latter case, alternative approaches seem to provide a better explanation for the phenomena. Without going into detail, we now mention some objections and some alternative approaches that will be taken into consideration at various instances in this thesis.

Several researchers remarked that the minimum principle is unrealistic (Hatfield & Epstein, 1985; Pomerantz & Kubovy, 1986). This argument is based on the idea that all possible interpretations must be generated by the perceptual system in order to select the simplest code. Further, it has been argued that the choice of regularities, involved in pattern descriptions, is rather arbitrary and is merely based on intuition. Moreover, it has been remarked that the measure of complexity, as employed within SIT, is not well-founded.

The above issues all concern the so-called *syntax* of the coding system. In addition, there are also questions with respect to the *semantics* of the coding system. This issue concerns the pattern aspects to which the coding system applies. Certain phenomena of perceptual organization seem to contradict the predictions according to the global-minimum principle. Kanizsa (1985) provided several examples of patterns for which the preferred interpretation did not seem to be covered by the global-minimum principle: in many cases, local features seem to determine the percept. This so-called *local-effect phenomenon* (Kanizsa, 1985) was demonstrated in the domain of visual occlusion and amodal completion. Kanizsa showed that in specific cases the perceived completion is not always the most regular shape. Other researchers, who have empirically tested the coding system (Boselie, 1988; Boselie & Wouterlood, 1989), also concluded that the global-minimum principle is untenable. In contrast with the notion of global simplicity, the latter researchers favour the so-called *local-cue approach* in which specific junction types (see also Ratoosh, 1949) are decisive in pattern interpretation. In addition, the Gestalt law of *good continuation* is generally held to be much more powerful than the tendency which favours the most regular shape (cf. Wouterlood & Boselie 1992; Kellman & Shipley, 1991). The tendency towards overall simplicity was also opposed by Rock (1983), who argued that the perceptual system seeks solutions in which the occurrence of a coincidental state of affairs is avoided. This coincidence-avoiding tendency is related to the *general-viewpoint principle* (Huffman, 1971) which holds that, when analyzing a scene, positions of objects and observers are assumed to be as general as possible. Both notions, in turn, are akin to what is generally known as the *likelihood principle*, originally formulated by Von Helmholtz (1867/1962), stating that the preferred perceptual organization reflects the most likely object or event. So, according to the likelihood principle, not the simplest but the *most probable* interpretation will be perceived.

The likelihood principle also underlies the currently influential notion of the so-called *nonaccidental properties* (NAPs) (Biederman, 1987), such as symmetry, parallelism and collinearity. These are properties of two-dimensional projections that, in many cases, also hold for the corresponding three-dimensional objects, or stating it otherwise, that have a high probability of occurrence under other positions of object or observer. These properties play an important role in the *Recognition By Components* (RBC) model of visual object recognition developed by Biederman (1987) which can be regarded as a prototypical approach in contemporary theorizing on object representation. As in many other models, within RBC certain a-priori defined characteristics of components, such as the curvature of axis, play an important role in the recognition of an object.

All in all, the likelihood principle and the aforementioned related concepts (coincidence, general-viewpoint principle, nonaccidental properties) nowadays are preferred to the minimum principle by many students of perception (cf. Pomerantz & Kubovy, 1986). An important additional reason for that preference probably is that the various operationalizations of the likelihood principle allow, more than those of the minimum principle, a modelling of the perceptual process. This, in turn, more easily permits implementations of the model in an artificial system. Although, in our view, the "implementability" of a model, inevitably constrained by contemporary technology, may be a criterion for its practical value, it certainly is not a criterion for its theoretical value. What has to be done, however, is to examine the impact of 'critical issues' regarding the SIT approach.

3 Simplicity of visual shape: an overview of the thesis

In this thesis an attempt is made to: (*i*) reply to drawbacks of the SIT coding language; (*ii*) reinterpret demonstrations against SIT; (*iii*) compare SIT to alternative approaches; (*iv*) test specific SIT predictions on a variety of stimulus material. These objectives will not be treated successively, but play a role at several places throughout this thesis. In the Epilogue of this thesis we will review each of these objectives in relation to the topics to which they apply.

The thesis has two main subdivisions. The first subdivision endorses our view that simplicity of visual shape is not restricted to a specific stimulus domain. It concerns a rough classification of the stimulus material on which specific hypotheses and claims are tested: Series (part 1), Surfaces (part 2), and Objects (part 3). The second subdivision in this thesis is of a more conceptual nature. This subdivision concerns four major themes related to the concept of simplicity: "quantification of simplicity", "unification by simplicity", "diversity by simplicity", and "components by simplicity". In the following, the latter themes will be introduced successively and their relation to "critical issues" will be clarified.

3.1 *Quantification of simplicity*

In past decades, several descriptive systems, or *coding systems*, have been proposed by various scientists (e.g. Simon & Kotovsky, 1963; Vitz, 1966; Vitz & Todd, 1969; Leeuwenberg, 1969, 1971; Restle, 1970, 1979; Jones & Zamostny, 1975; Deutsch & Feroe, 1981). Although not all coding systems were designed for visual patterns, each of them transposes a pattern into a symbolic representation. Within SIT, a visual pattern is represented by a symbol series referring to, for example, subsequent lines and angles in the contour of a visual pattern. Then, by means of coding rules, the initial series can be reduced to a shorter series or code. This reduction proceeds by extracting as much regularity as possible from such an initial series. These regularities are based on identities between the elements in the symbol series. Recently, new theoretical insights (Van der Helm, 1988; Van der Helm & Leeuwenberg, 1991) have led to a formalization of the concept of regularity, which, in turn, affects the quantification of simplicity. This formalization answers some of the criticism that has arisen against the SIT coding. The starting point of this formalization is the concept of *accessibility*, stating that appropriate coding rules are characterized by so-called *holographic regularity* and *transparent hierarchy*. Holographic regularities are regularities constituted by identity structures in which all substructures express the same kind of regularity. The concept of transparent hierarchy demands that groupings due to different regularities are compatible with each other and can be superimposed on each other. These concepts will be clarified in further detail in Chapter 1. Considering all possible regularities in a pattern it appears that only a few regularities possess the qualities of holography and transparency (Van der Helm & Leeuwenberg, 1991). These regularities form the kernel of the regularities that have been used since SIT's conception (Leeuwenberg, 1969; 1971), namely Iteration, Symmetry and Alternation. Van der Helm and Leeuwenberg (1986, 1991) also replied to another objection stated in the previous paragraph, namely that the minimum principle is thought to be unrealistic, because all possible encodings have to be generated separately. They showed that, by means of the concept of accessibility plus a mathematical technique called the shortest path method, the simplest code can be found without generating each possible code separately.

Before the concept of accessibility had been introduced in the Structural Information Theory, several measures of structural information were considered. The measure that was most commonly used in past decades will be referred to as I_{old}-load. This load was meant to reflect the amount of storage space needed to represent a code. We will argue that the I_{old}-load gives rise to several conceptual problems. For example, in Chapter 1 we state that by way of this load incomparable entities contribute to the complexity of that code (see also Hatfield & Epstein, 1985). Beside such conceptual problems, our view is that the semantical implication of a code (i.e. an interpretation) should not be judged on the basis of the required memory space but, psychologically more meaningful, on the basis of the semantical content of the code (i.e. the description of regularity). The accessibility criterion, referred to above, paved the way for a new information load which overcomes the problems with the I_{old}-load. This new information load (to be referred to with I_{new}-load) will be introduced in Chapter 1.

The I_{old}-load, the I_{new}-load, and a few alternative proposals, have been tested on serial patterns. In the experiment, subjects had to indicate their preferred organization of a symbol series in a paired-comparison task. In that task, two possible organizations were given by means of a clustering of symbols. Each organization was derived from a specific encoding of the series. Evidently, the complexities according to each of the tested information loads were crucial in the testing procedure. It appeared that, of all proposed information loads, the I_{new}-load in most cases predicted the preferred organization correctly, i.e. it was the lowest for the most preferred interpretation. We used serial patterns, because these stimuli are relatively close to the coding language. In this way possible errors, due to the semantic mapping were minimized. An implication of the new complexity measure is that it predicts more *local* organizations than the earlier measures did. That is, in many cases, the predicted subdivisions in symbol series have a smaller span under the new information load. It is important to note, however, that these local organizations are induced by a measure of *global* simplicity.

3.2 *Unification by simplicity*

Whereas the previous theme mainly concerned the syntax of the coding language, the present theme deals with the semantics of the language. That is, the question now is to which pattern aspects simplicity applies. We will focus on line-drawn patterns that are readily perceived as a composition of surfaces either juxtaposed to each other in a mosaic like fashion or arranged in depth, revealing a partial occlusion of one of the surfaces. In this domain, counter examples of the tendency towards global simplicity, referred to as the local-effect phenomenon, have been given (Kanizsa, 1985; Rock, 1983; Boselie, 1988; Boselie & Wouterlood, 1989).

In Chapter 2, we argue that not only the simplicity of the shapes must be considered in determining the complexity of an interpretation, but also their relation with the pattern. In our view, this relational aspect is of decisive importance in the *acquisition* of an interpretation. To that end, a distinction is made between the *memory complexity* and the *perceptual complexity* of an interpretation. Whereas the memory complexity specifies the amount of information that is needed to store an interpretation into memory, the perceptual complexity is based on the relationship between the pattern and its interpretation. In for example Buffart et al. (1981) and Boselie (1988) the memory complexity was used in order to predict pattern interpretations. They dealt with the old measure of information load, which fitted with the idea of storage capacity. The perceptual complexity, as proposed in Chapter 2, considers three aspects of an interpretation which jointly determine the perceptual complexity of an interpretation: *shape*, *position* and *occlusion*. These components are embedded in three different types of structure, indicated by the *internal structure*, the *external structure*, and the *virtual structure*, respectively. In general, regularities between pattern elements have a *binding effect* on those elements. Because of that, regularities in the internal structure support a specific interpretation, whereas regularities in the external structure weaken that interpretation. The virtual structure concerns the elements that are not present in the distal stimulus, but are present in the interpretation of that stimulus, i.e. the occluded part of a shape. We hypothesize that the more of a shape is occluded, the weaker the completion tendency towards that specific shape will be. Each of the three structures independently affects the preference of perceptual interpretations of occlusion patterns, and their complexities can all be expressed in terms of structural information. We hypothesize that the sum of the perceptual complexities of the three structures determines the *total perceptual complexity* of an interpretation and that the total perceptual complexity of the most preferred interpretation is lower than that of any other interpretation. This proposal has been tested on a large variety of critical patterns and data stemming from three different papers: Buffart, Leeuwenberg, and Restle (1981), Boselie (1988), and Boselie and Wouterlood (1989). The first paper has been selected because it claims the applicability of SIT to completion patterns. The latter two papers have been chosen because they contain a large number of patterns that appeared to be in contradiction with predictions done by SIT. The experimental procedure in each of those studies was the same: given a pattern, subjects were asked to draw the contours of their spontaneous pattern interpretation on a piece of paper. Among others, it appeared that for 95% of the patterns the total perceptual complexity correctly predicts the most preferred interpretation. $I_{internal}$, $I_{external}$, and $I_{virtual}$ correspond, to a certain extent, to three well-known tendencies in the domain of visual occlusion, namely the goodness of form, the avoidance of coincidence, and the good-continuation principle. These different tendencies are now unified by the notion of simplicity, and therefore devaluate to secondary explanatory concepts.

3.3 *Diversity by simplicity*

In line with the minimum principle, it is assumed that the perceptual system generates multiple interpretations and that the simplest one is selected. Already Herbart (1850) suggested such a *competition* between different interpretations. According to Herbart the dominant percept may vary in strength, depending on the attractiveness of the competing interpretations. In Chapters 3 and 4, an answer is sought, by means of various experiments, to the question whether these interpretations are actually generated by the perceptual system. We focus on two completion tendencies in case of visual occlusion. One tendency leads towards the simplest completed shape (a global completion) and the other tendency leads to a shape for which the completion itself is as simple as possible (a local completion). In line with Herbart's (1850) ideas and the findings of Mens and Leeuwenberg (1988) we hypothesize that both completions are generated and subsequently compete with each other.

In Chapter 3 we reason that the competition emerges from the interdependency of the strengths of the completion tendencies. Two experimental paradigms are employed on ambiguous occlusion patterns (i.e. allowing different global and local completions) to test these strengths. In one experiment, subjects were asked to draw their spontaneous pattern interpretation, like in Buffart, Leeuwenberg, and Restle (1981), Boselie (1988) and Boselie and Wouterlood (1989). A second experiment concerned a simultaneous-matching task, partly adopted from Gerbino and Salmaso (1987). The first experiment clearly demonstrates the relevance of both global and local completions. In the second experiment matching a shape with an occluded shape in an ambiguous occlusion pattern showed significantly higher response times than matching it with an unoccluded shape. Furthermore, the spontaneous preferences for either global or local completions in the drawing task showed a significant correlation with the response times on the same set of patterns in the simultaneous-matching task. We argue that the data support the notion that the preference for either a global completion or a local completion is the result of a competition between interpretations. It will also be discussed how the relative preference for a completion can be predicted by the quantifying model based on simplicity as proposed in Chapter 2.

In Chapter 3, the competitive aspect between completions gains support by the finding that the strength of a specific global completion depends on the strength of the local completion and vice versa. This interdependency suggests the processing of both global and local completions. In Chapter 4, we aim at further converging evidence for the generation of multiple completions by means of the primed-matching paradigm (Beller, 1971). This paradigm is based on the effect of a prime on matching a pair of items, and turned out to be a useful tool in assessing a subject's representation. In general, the responses appeared to be facilitated by a representational similarity between a prime and a matching pair of test shapes (Beller, 1971; Sekuler & Palmer, 1992). In their study, Sekuler and Palmer (1992) used partly occluded two-dimensional shapes as primes, and unoccluded two-dimensional shapes as test shapes. In the case that the test shapes corresponded to the preferred completion of the occluded shape in the prime, they found a higher facilitating effect than in the case that the test shapes corresponded to the literal (mosaic) interpretation. In Chapter 4, various occlusion patterns for which the global completion is most prevalent (a subset of the patterns used in Chapter 3) were used as primes. The priming effects on global, local, and anomalous completions were investigated. In general, it appears that the priming effects on the global completions are the highest and that the priming effects on the anomalous completions are the lowest, whereas the priming effects on the local completions take an intermediate position. We conclude that beside the generation of the global completions also the local completions are generated. A second experiment controls for the possibility that the priming effect on the global completion "spreads out" to the local completion. This time many different completions have been tested as well. The results confirm the special status of the global and local completions.

3.4 *Components by simplicity*

We now take up the debate concerning the minimum principle versus the likelihood principle. This time the discussion will be in the context of object representations. An important aspect of representations derived from the minimum principle is that their descriptive components are a *result* of the simplest representation. This contrasts with models in which the likelihood of occurrence is an important concept such as, for example, the Recognition By Components model of Biederman (1987). In that model, descriptive components of certain simple objects, called geons, are defined *a priori* by means of the nonaccidental properties.

In Chapter 5, object classifications according to RBC and SIT are compared with each other. In this comparison, special attention is given to what is generally conceived as the axis of an object. Within RBC the axis of an object is determined by both structural and metrical criteria. In our view, the specification of axes according to that combination of criteria is rather unclear. We argue that the more the axis accounts for *structural constancy* the more it agrees with SIT, and the better it predicts perceptual classification. The latter is verified by means of a classification task. In Chapter 5, we further show that the likelihood of a nonaccidental property conflicts with a strict probability calculus and has been actually based on regularity itself, which in fact is in line with the minimum principle.

As mentioned, according to SIT the descriptive components of an object emerge from the simplest representation of that object. In contrast with RBC, these descriptive components in principle may have any possible shape, as long as they account for as much structural constancy as possible. A further important aspect of SIT's object representation is the possible *hierarchical relationship* between its descriptive components. Within such an hierarchical description, the higher level is referred to as the *superstructure* of an object, whereas the lower levels are referred to as the *subordinate structures*. In line with Leeuwenberg and Van der Helm (1991), we hypothesize that descriptive components at the superstructural level dominate the descriptive components at the subordinate level, i.e. the *superstructure-dominance hypothesis*.

In Chapter 6 the above hypothesis has been tested by means of the primed-matching paradigm. Two experiments are presented. In the first experiment the test shapes were constituted by two-dimensional line drawings of the objects, whereas the primes were two-dimensional faces of the objects corresponding to either the superstructure or the subordinate structure of the objects. Two priming conditions were applied: a literal and a frontal condition. In the literal condition the prime had exactly the same shape as the corresponding surface in the object drawing. In the frontal condition the same surface was used as a prime, but now presented in the frontal-parallel plane. It appeared that priming the superstructure facilitates matching of objects more than priming the subordinate structure. This difference in facilitation was strongest for the frontal primes. In a second experiment it has been investigated whether the differences in priming effect could be attributed to a difference in the way the surfaces were embedded in the object drawings. This time, the primes were constituted by one of the objects, whereas the test pairs were made up by surfaces. Again there were facilitating effects for both the superstructure and the subordinate structure. However, there were no differential effects between the superstructure and the subordinate structure. We conclude that the data support the superstructure-dominance hypothesis and that they cannot be attributed to differences in embeddedness. The confirmation of the superstructure-dominance hypothesis supports SIT's hierarchical decomposition of objects into components, which is based on the concept of simplicity in visual shape.

PART 1

SERIES

"Quantification of Simplicity"

Chapter 1

Serial pattern complexity: irregularity + hierarchy

Abstract
In perception research, various models have been designed for the encoding of, for example, visual patterns, in order to predict the human interpretation of such patterns. Each of these encoding models provides a few coding rules to obtain codes for a pattern, each code expressing regularity and hierarchy in that pattern. Some of these models employ the minimum principle which states that the human interpretation of a pattern is reflected by the simplest code for that pattern, i.e. the simplest code according to a given complexity metric. In this paper a new complexity metric is proposed. This metric is based on a formal analysis of the concept of regularity. Some conclusions of this analysis are sketched. The new metric does not depend on artifacts of the coding rules. It accounts for the amounts of irregularity and hierarchy as represented in a code of a pattern, such that these two amounts can be added to determine the complexity of a code. An experiment is discussed that shows that the new metric performs significantly better than metrics used previously. In particular, the new metric predicts more local pattern organizations than the old metrics. This implies that various local pattern organizations do not falsify the minimum principle anymore.

1 Introduction

Regularity is a rather intuitive concept that seems to defy formal description. This aspect becomes relevant when regularity explicitly plays a crucial role, as it does in many formal models of perception (Simon & Kotovsky, 1963; Vitz, 1966; Vitz & Todd, 1969; Leeuwenberg, 1969, 1971; Garner, 1970; Restle, 1970, 1979; Jones & Zamostny 1975; Deutsch & Feroe, 1981; Palmer, 1983; Leyton, 1986a,b). These models are designed to explain the phenomenon that although, in principle, a pattern can be interpreted in many ways, usually one interpretation is preferred (see Figure 1 for an example in visual shape perception). This preference is assumed to be guided by the regularity that is present in a pattern. For instance, in Figure 1, the usually preferred interpretation is assumed to be induced by the repetition, i.e. the regular occurrence of

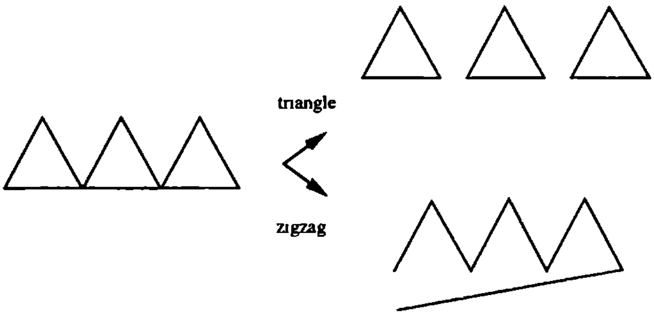


Figure 1. In visual shape perception, a major problem is how to predict the preferred interpretation of a pattern which, in principle, can be interpreted in many ways. Here, two possible interpretations of a line drawing are visualized. Usually, the triangle interpretation is preferred, not the zigzag interpretation.

the triangle part. This assumption is in line with the minimum principle (Hochberg & McAlister, 1953) which, historically, fits in with the tradition of Gestalt psychology (Wertheimer, 1912; Kohler, 1920; Koffka, 1935). The minimum principle states that the preferred interpretation of a pattern is reflected by the simplest description of that pattern. Now, for each model mentioned above, it holds that patterns are described in terms of a formal language designed to express regularity in patterns. Yet, the models show great variety in the formal definition and in the justification of the complexity metric that is used to decide which of the possible descriptions is the simplest one. The fact that, for many of these metrics, the predictions are rather similar (Simon, 1972) is, in our view, not very surprising since, for all metrics, it holds more or less that a pattern description is simpler if it expresses a larger amount of regularity in the pattern. However, in each model, regularity is incorporated and discussed only in terms of examples showing only a few kinds of regularity (like repetitions and symmetries). These few kinds of regularity may be relevant in perception, but represent only one choice out of many possible kinds of regularity. This choice may be plausible and may be even empirically supported, yet it is not the same for all models. That is, as long as regularity as such is not specified, one can hardly assign psychological significance to a specific choice concerning pattern descriptions and complexity metrics (Simon, 1972). In the present paper, we will propose a solution to this problem, which may be introduced briefly as follows.

In the paper of Van der Helm & Leeuwenberg (1991), the intuitive concept of regularity has been formalized within the framework provided by the structural information model of Leeuwenberg (1969, 1971). This model is an encoding model, focusing mainly on visual shape perception. In this model, a pattern can be described, in several ways, by means of coding rules expressing regularity in the pattern. In agreement with the minimum principle and given a complexity metric, the simplest pattern description, or simplest code, is assumed to reflect the preferred interpretation of the pattern. So, the structural information model consists of the minimum principle plus an operationalization of the minimum principle, and the operationalization consists of coding rules plus a complexity metric. In the present paper, we will not compare Leeuwenberg's model with other models (for a review on these topics and for references to related literature, see Van der Helm & Leeuwenberg, 1991). Instead, we will focus primarily on the choice of a psychologically significant complexity metric, on the basis of an analysis of the intuitive concept of regularity. To that end, first we will go into the structural information model in some detail. Second, we will sketch the results of an analysis of regularity. The actual analysis is presented in Van der Helm & Leeuwenberg (1991). Third, we will propose a new metric of complexity. This metric stems from the analysis of "regularity". Finally, we will discuss an experiment that has been designed to test how well preferred interpretations can be predicted by the new complexity metric. In the experiment, subjects had to indicate their preference for one out of three segmentations of patterned sequences of, for example, black and white dots.

2 The structural information model

The encoding of visual patterns, as performed in the structural information model (Leeuwenberg, 1969, 1971), proceeds as follows. In order to describe regularity in a pattern, the pattern is first represented by a symbol series. For instance, in Figure 2, the contour of the pattern consists of subsequent angles and line segments, each of which is labelled with a symbol. Angles or line segments of equal size are labelled with an identical symbol. These symbols will be called pattern symbols, indicating that a symbol refers only to a pattern part and not to its meaning in, for example, the Roman alphabet. Now, tracing the contour in clockwise direction would yield the symbol series 'kalckalckalc', representing the pattern. Note that, in theory, a pattern is not considered to be mapped onto a symbol series. On the contrary, the symbol series has to be such that the pattern can be reconstructed by substituting the actual sizes of angles and line segments for the pattern symbols (cf. Leyton, 1986a,b). This substitution is called the semantic mapping from the symbol series onto the pattern. The semantic mapping as such may already give rise to several questions, for instance with respect to the number of possible symbol series by which a pattern can be represented. In the present paper, however, we will not deal with these questions. In particular, in the experiment to be discussed in this paper, we chose stimuli for which the semantic mapping does not raise problems.

The actual encoding consists of describing regularity in terms of identical symbols in the symbol series which, because of the semantic mapping, corresponds to the regularity in the pattern. In the structural information model, only three classes of regularities play an essential role, namely iterations, symmetries, and so-called alternations. Each of these three classes is described by means of one coding rule. As we will argue in the next section, these three coding rules are indeed the proper ones to be used according to the formalization of regularity as elaborated in Van der Helm & Leeuwenberg (1991). Next, we will proceed by giving the definitions of these coding rules, and the way in which these coding rules can be applied to symbol series.

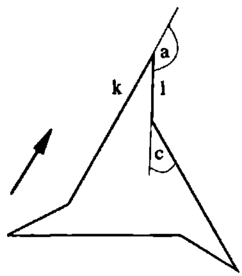


Figure 2. Tracing the contour of the pattern (the arrow indicates the starting point and direction) yields the symbol series 'kalckalckalc'. This symbol series represents the subsequent angles and line segments in the contour so that, by substituting the actual values for the symbols, the pattern can be reconstructed. According to Leeuwenberg's structural information model, interpretations of the pattern can be obtained by encoding the symbol series.

First, the Iteration rule which can be applied to express that a series contains successive identical symbols, is defined as follows:

$$\text{kkk...kk} \quad \rightarrow \quad \text{N*(k)}.$$

The expression on the right-hand side is called an I-form, in which N equals the number of symbols 'k' in the series at the left-hand side (N≥2), while '(k)' is called the I-argument. For instance, according to the Iteration rule, the series 'aaaaa' can be encoded into '5*(a)'.

Second, the Symmetry rule which can be applied to express that a series contains pairs of identical symbols, nested around a so-called pivot, is defined as follows:

$$k_1\ k_2\ \dots\ k_n\ p\ k_n\ \dots\ k_2\ k_1 \rightarrow S[(k_1)(k_2)\dots(k_n),(p)].$$

The expression on the right-hand side is called an S-form, in which '(p)' is the pivot, while the series '$(k_1)(k_2)\dots(k_n)$' is called the S-argument and consists of elements '(k_i)', where $i=1,2,\dots,n$ ($n\geq 1$). For instance, the series 'kapmpak' can be encoded as 'S[(k)(a)(p),(m)]'.

Third, there is the Alternation rule which can be applied to express that a series contains successive subseries that either all begin or all end identically. Both cases are given in the following definitions:

$$kx_1\ kx_2\ \dots\ kx_n \rightarrow <(k)>/<(x_1)(x_2)\dots(x_n)>,$$

and

$$x_1k\ x_2k\ \dots\ x_nk \rightarrow <(x_1)(x_2)\dots(x_n)>/<(k)>.$$

The expression on the right-hand side is called an A-form, in which the series '$(x_1)(x_2)\dots(x_n)$' is called the A-argument and consists of elements '(x_i)', where $i=1,2,\dots,n$ ($n\geq 2$). For instance, the series 'arasat' can be encoded as '<(a)>/<(r)(s)(t)>', while the reversal of that series, i.e. 'tasara', can be encoded as '<(t)(s)(r)>/<(a)>'. In applying the coding rules to a symbol series, one should take notice of the following two aspects.

First, in the definition of the coding rules, the symbols are considered to be variables standing for arbitrary subseries (with identical symbols standing for identical subseries). This implies that the coding rules can be applied not just to express identity of single symbols but, in general, to express the identity of subseries in a series. For instance:

ababab → 3*(ab),

and

badpqvwpqbad → S[(bad)(pq),(vw)].

Note that the parentheses in an I-, S-, or A-form (which we shall call an ISA-form) yield an unambiguous notation. Any subseries between parentheses in an ISA-form is called a chunk. It should be noted that the pivot in an S-form is a chunk which, as a limiting case and without distorting the symmetrical structure, may be "empty". This implies that, for instance, the series 'abppab' can be encoded into an S-form, denoted by 'S[(ab)(p)]'.

Second, the subseries inside a chunk in an ISA-form can be encoded just like any symbol series, for instance:

bapabapa → 2*(bapa) → 2*(b S[(a),(p)]),

and

aabppaab → S[(aab)(p)] → S[(2*(a)b)(p)].

In such cases, the ISA-forms are said to be hierarchically nested. Similarly, but less trivially, a hierarchical nesting of ISA-forms may result in the following way. Whereas an I-argument consists of only one chunk, an S- or an A-argument is, in general, a series consisting of several chunks. Such a chunk series can be encoded the same way as a symbol series. Consider, for instance, the following encoding:

ababbaba → S[(a)(b)(a)(b)] → S[2*((a)(b))].

In this example, the S-argument '(a)(b)(a)(b)' constitutes a chunk series 'xyxy' in which the chunk 'x'='(a)' and the chunk 'y'='(b)'. Just like a symbol series, the chunk series 'xyxy' can be encoded by applying the coding rules. This yields, for example, the code '2*(xy)' which, by substituting 'x'='(a)' and 'y'='(b)', yields the code '2*((a)(b))' as given in the example. Similarly, the argument of an A-form can be encoded. Whereas the symbol series is said to represent the lowest hierarchical level, an I-, S-, or A-argument is said to represent a higher hierarchical level, and the encoding of an S- or A-argument leads to still higher hierarchical levels.

Now that we have considered the way in which the coding rules can be used to encode symbol series into codes, we can go into the meaning of the codes in more detail. First of all, by expressing identities in a series, a code provides a description of regularity in that series. However, this is not the ultimate meaning of a code. The ultimate meaning of a code is constituted by the fact that a code provides a means of obtaining a classification and an organization of the series, which together reflect an interpretation of the pattern that is represented by the series. This may be illustrated as follows.

First, for the four-symbol series 'aaba', the code '2*(a)ba' expresses just the identity of the first and second symbols, which corresponds to all identity in a four-symbol series like 'ppqr'. Thus, 'ppqr' can be seen as a representative of the class of symbol series to which 'aaba' belongs according to the code '2*(a)ba' (cf. Collard & Buffart, 1983). In general, such a class representative can be found as follows. First, replace all pattern symbols in the code by arbitrary but different symbols; then, decode the code. For instance:

aaba → 2*(a)ba → 2*(p)qr → ppqr.

Note that, according to another code, the symbol series 'aaba' belongs to another class. For instance:

aaba $\rightarrow$ aS[(a),(b)] $\rightarrow$ pS[(q),(r)] $\rightarrow$ pqrq.

According to this classification, the second and fourth symbols are taken as being identical. Whether 'aaba' is encoded and classified in the first way or in the second way, is determined by some complexity metric. That is, in agreement with the minimum principle, the humanly preferred interpretation of a pattern is assumed to be reflected by the simplest code for the pattern. We will discuss complexity metrics in a later section.

Second, a code not only prescribes a classification, but also an organization of a pattern. For the series 'ababab', the code '3*(ab)' expresses that 'ababab' is similar to 'yyy' where 'y'='ab'. So, the code can be said to induce the organization '(ab)(ab)(ab)' in the series, i.e. a partitioning of the series into chunks. Such organizing in terms of chunks will be called a chunking (cf. Geissler, Klix & Scheidereiter, 1978). In general, the chunking induced by an ISA-form can be found by decoding the ISA-form without removing the parentheses in the ISA-form, e.g.:

badpqvwpqbad $\rightarrow$ S[(bad)(pq),(vw)] $\rightarrow$ (bad)(pq)(vw)(pq)(bad),

and

hkghkpq $\rightarrow$ <(hk)>/<(g)(pq)> $\rightarrow$ (hk)(g)(hk)(pq).

As illustrated in Figure 3, a chunking of a symbol series reflects an organization in the pattern that is represented by the symbol series. Note that, perceptually, 'ababab' does indeed seem to consist of the three parts '(ab)' in line with the chunking '(ab)(ab)(ab)' as induced by the code '3*(ab)', but that 'abababpqqp' seems to consist of the parts 'ababab' and 'pqqp' which does not imply a chunking in the above sense. Yet the latter organization is relevant too (Leeuwenberg & Van der Helm, 1991) and will be called

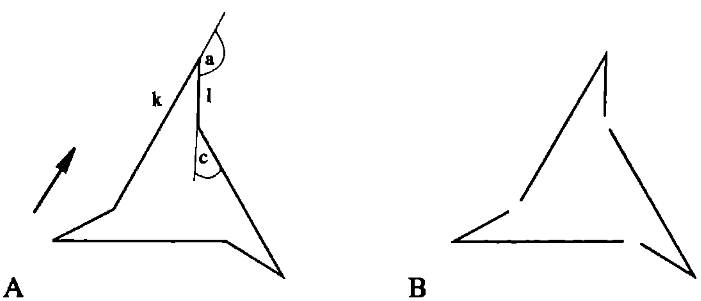


Figure 3. If the pattern in (A) is represented by the symbol series 'kalckalckalc' then, according to the structural information model, this symbol series can be encoded into '3*(kalc)'. This code induces, in the symbol series, the organization '(kalc)(kalc)(kalc)' which, in the pattern, corresponds to the organization as shown in (B).

clustering. One aspect of clustering is that each ISA-form is considered to induce a cluster containing all the chunks needed to construct that ISA-form. For instance, for (sub-)series 'ababab', the I-form '3*(ab)' groups the three chunks '(ab)' into one cluster '((ab)(ab)(ab))'.

Another aspect of clustering is related to the intrinsic character of a regularity structure, and has consequences for S- and A-forms only (I-forms are too simple to show such an extra aspect). First, we will discuss the S-forms. We stated that an S-form expresses that a symbol series contains pairs of identical subseries nested around a pivot. For instance, the series 'abcpbca' can be encoded into the S-form 'S[(a)(bc),(p)]', inducing the chunking '(a)(bc)(p)(bc)(a)'. Now, with respect to that chunking, the S-form can also be said to induce a tri-partitioning into the S-argument '(a)(bc)', the pivot-chunk '(p)', and the reversed S-argument '(bc)(a)'. Therefore, the S-form will be said to induce the grouping of the chunks in the S-argument into one cluster '((a)(bc))', as well as the grouping of the chunks in the reversed S-argument into one cluster '((bc)(a))'. This clustering can be indicated in the chunk series by '((a)(bc))(p)((bc)(a))'. We also stated that an A-form expresses that a symbol series contains successive subseries which either all begin or all end identically. Let us focus on the "all-begin-identically"-case (the "all-end-identically"-case is completely analogous). For instance, the series 'abpqabrsabt' can be encoded by the A-form '<(ab)>/<(pq)(rs)(t)>', which induces the chunking '(ab)(pq)(ab)(rs)(ab)(t)'. Now, in that chunking, each of the above mentioned "successive subseries" is chunked into a pair of chunks, called an A-pair. So, each A-pair constitutes a unit that is characteristic for the regularity described by the A-form. Moreover, as we will see later on, the A-pairs are essential for understanding the hierarchical character of the A-rule. Therefore, the A-form above will be said to induce a clustering by grouping each A-pair into a cluster, which can be indicated in the chunk series by '((ab)(pq)) ((ab)(rs)) ((ab)(t))'. So, in summary, besides a chunking, an ISA-form also induces a clustering based on that chunking: each ISA-form induces one cluster consisting of all chunks in that chunking; an S-form induces two further clusters, namely the S-argument and the reversed S-argument; an A-form induces further clusters by grouping each A-pair into a cluster.

The perceptual organization of a pattern, as induced by a code of the pattern, will be said to consist of the combination of the chunking and the clustering as induced by that code. Furthermore, the dominant segmentation in a perceptual organization of a pattern is said to be the segmentation that consists of at least two, maximally sized, segments (chunks or clusters) present in that perceptual organization. As an illustration, we reconsider the pattern in Figure 1. The pattern in Figure 1 can be represented by a symbol series in several ways; in this example, we will focus on the two most relevant representations (see Figure 4). Remember that a symbol series represents a pattern, if that pattern can be reconstructed from the symbol series by substituting the actual sizes of angles and line segments for the pattern symbols. One way to represent the pattern, is by means of the symbol series 'kakakakkakakakkakakak' (see Figure 4A). For all of the complexity metrics to be discussed later on, the simplest code of this symbol series is '3*(k 3*(ak))'. This code yields the chunking '(kakakak)(kakakak)(kakakak)' as the dominant segmentation, corresponding to the triangle interpretation of the pattern. Another way to represent the pattern, is by means of the symbol series 'kakbkakbkakbcl' (see Figure 4B). The simplest code of this symbol series is '3*(<(k)>/<(a)(b)>)cl'. This code yields the clustering '(kakbkakbkakb) c l' as the dominant segmentation, corresponding to the zigzag interpretation of the pattern. Now, the code that reflects the triangle interpretation is simpler than the code that reflects the zigzag interpretation and, indeed, the triangle interpretation is usually preferred.

3 The concept of regularity

In Van der Helm & Leeuwenberg (1991), a formalization of the intuitive concept of regularity has been given within the framework provided by the structural information model. In this section, we will summarize this formalization in a nonformal way, i.e. we will, by means of examples, give a gist of the model in order to put the new complexity metric in a proper perspective. The formalization is twofold: first, the intrinsic character of regularity is specified by the formal notion of holographic regularity; second, the way in which cases of regularity can be related hierarchically is specified by the formal notion of transparent hierarchy. In this section, these two formal notions will be discussed successively, after which several psychologically relevant implications will be discussed.

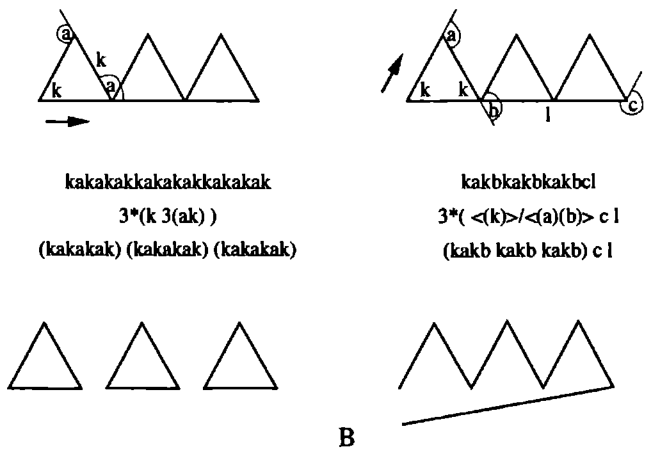


Figure 4. The pattern in Figure 1 can be represented in two ways by means of the symbol series shown in (A) and (B). For each symbol series, the simplest code is shown with the induced dominant segmentation in the symbol series and, correspondingly, in the pattern. The code in (A) is simpler than the code in (B) and, indeed, reflects the usually preferred triangle interpretation.

3.1 *Holographic regularity*

As we have seen, the structural information model represents a visual pattern by means of a symbol series in which the symbols refer to pattern parts (the semantic mapping). Therefore, an interpretation of the pattern is considered to be reflected in the classification and organization of the symbol series which, because of the semantic mapping, corresponds to a classification and an organization of the pattern. By using coding rules, the symbol series is classified and organized on the basis of a hierarchical description of regularity in the symbol series. Note that the symbol series only represents information about the order and the identity of pattern parts. So, in this context, the formalization of regularity can only be based on arrangements of identical symbols in a symbol series. Now, the formalization proceeds as follows.

First, any arrangement of identical symbols in a series is formally called a case of regularity, no matter whether or not it reflects something intuitively regular. That is, we start with all theoretically possible cases, and e.g. a repetition of a specific something a specific number of times (such as nine times the symbol 'p') is just one of these cases. So, the arrangement of identical symbols in a series is formally called a case of regularity, not only for series like 'aaaa' and 'abccba', but also for series like 'kpfzpkf' and 'kyppzfkf. Now, for example, in the series 'yy', the arrangement of identical symbols is formally denoted by the expression (1)=(2), which simply indicates that the first symbol is identical to the second symbol. The expression (1)=(2) is called an identity. Note that the same identity denotes the arrangement of identical chunks in, for example, the chunk series '(ab)(ab)'. A set of identities is called an identity structure, if the set meets some formal requirements. One of the requirements is that the identities in the set are ordered. For instance, the case of regularity reflected by the arrangement of identical symbols in the series 'aaaa', is formally denoted by the identity structure {(1)=(2),(2)=(3),(3)=(4)} which consists of three identities in the given order.

Second, all different cases of regularity are categorized into kinds of regularity, which may be illustrated as follows. For the series 'abab', the arrangement of identical symbols can be denoted by, among others, the identity structure {(1 2)=(3 4)} which indicates that the two subseries 'ab' are identical. In this identity structure, each of the two subseries 'ab' is taken as one unit, just like when the series 'abab' would be chunked into the chunk series '(ab)(ab)'. In other words, the identity structure expresses that 'abab' is the same as 'yy' under the substitution 'y'='ab'. Now, observe that, in the series 'yy' or '(ab)(ab)', the identity structure {(1)=(2)} actually expresses the same as the identity structure {(1 2)=(3 4)} in the symbol series 'abab', namely the identity of the two subseries 'ab'. Therefore, although these two identity structures describe different cases of regularity, they are said to describe the same kind of regularity (namely, in words, a repetition of two times an arbitrary something). Note that, formally, two times an arbitrary something is a different kind of regularity from that of three times an arbitrary something. In summary, a repetition a of specific something a specific number of times is a case of regularity, and a repetition of an arbitrary something a specific number of times is a kind of regularity. As we will argue next, repetition in general (an arbitrary something an arbitrary number of times), is a case of holographic regularity.

Above, we saw that an identity structure reflects a property of a series, namely identity of elements in that series. Now, holographic regularity specifies a possible property of identity structures. Metaphorically, the notion of holographic regularity may be illustrated by a jigsaw puzzle that is to represent a landscape consisting of a green lawn and a sky with clouds. Then, each green piece in the disordered set of pieces can be classified as a lawn-piece, since such a piece shows the holographic property of having the same color as the entire lawn. In our view, such a holographic property applies quite well to the intuitive concept of regularity. For instance, a repetition of something is a repetition no matter whether the number of times that the something is repeated is large (analogous to the jigsaw lawn) or small (analogous to the jigsaw piece). The formal notion of holographic regularity has been elaborated as follows.

An identity structure can be seen as a chain of identities, because it is an ordered set. This implies that one can define a substructure of an identity structure as an ordered subset of successive identities in the identity structure or, in other words, as a subchain. For instance, the earlier-mentioned identity structure {(1)=(2),(2)=(3),(3)=(4)} has five substructures, namely {(1)=(2),(2)=(3)}, {(2)=(3),(3)=(4)}, {(1)=(2)}, {(2)=(3)},

A		B	
rstptsr		*kpfkfp*	
{(1)=(7) , (2)=(6) , (3)=(5)}		{(1)=(4) , (2)=(6) , (3)=(5)}	
{(1)=(7) , (2)=(6)}	{(2)=(6) , (3)=(5)}	{(1)=(4) , (2)=(6)}	{(2)=(6) , (3)=(5)}
rs . . . sr	*. st . ts .*	*kp . k . p*	*. pf . fp*

Figure 5. Holographic regularity. In (A) the arrangement of identical symbols in the series 'rstptsr' is denoted by an identity structure consisting of three identities. Below this identity structure are shown its two substructures consisting of two identities each. Each of these substructures is visualized by substituting, in 'rstptsr', a dot for those symbols to which the substructure does not apply. In (B) exactly the same procedure has been followed for the series 'kpfkfp'. In (A) both substructures reflect the same arrangement of identical symbols. That is, the two symbols 'r' and the two symbols 's', in the visualization of the first substructure, are arranged in the same way as the two symbols 's' and the two symbols 't' in the visualization of the second substructure In other words, both substructures describe the same kind of regularity, which is precisely the reason that the identity structure shown at the top is said to describe a holographic kind of regularity. In contrast, in (B) the two substructures clearly do not reflect the same arrangement, i e do not describe the same kind of regularity, so that the identity structure at the top does not describe a holographic kind of regularity.

and {(3)=(4)} (see also Figures 5 and 7). Now, analogous to the jigsaw puzzle and expressed simply, an identity structure is said to describe a holographic kind of regularity if its substructures all describe the same kind of regularity (see also Figure 5).

Observe the recursive character of the notion of holographic regularity; if an identity structure describes a holographic kind of regularity, then any of its substructures describes a holographic kind of regularity too, since all substructures of the identity structure (including the substructures of a substructure) describe the same kind of regularity. This recursive character is essential in elaborating the formal implications of the notion of holographic regularity. Without going into details, these formal implications can be summarized as follows (for the details, see Van der Helm & Leeuwenberg, 1991).

Instead of considering all possible identity structures (an infinite number), it is more suitable and suffices to consider only all identity structures consisting of precisely three identities (also an infinite number). One can prove, first, that the infinite number of different cases of regularity, as described by these identity structures consisting of three identities, can be categorized into precisely 648 different kinds of regularity and, second, that only 20 of these 648 kinds of regularity are holographic. Then, because of the recursive character of holographic regularity, one can prove two further things. First, for each of those 20 holographic kinds of regularity, a representative identity structure (consisting, as before, of three identities) can be generalized uniquely into an identity structure consisting of an arbitrary number of identities (analogous to simply increasing the number of times in a repetition). Each of these 20 generalized identity structures is called a case of holographic regularity. Second, one can prove that these 20 cases constitute all possible cases of holographic regularity. Figure 6 shows some of these.

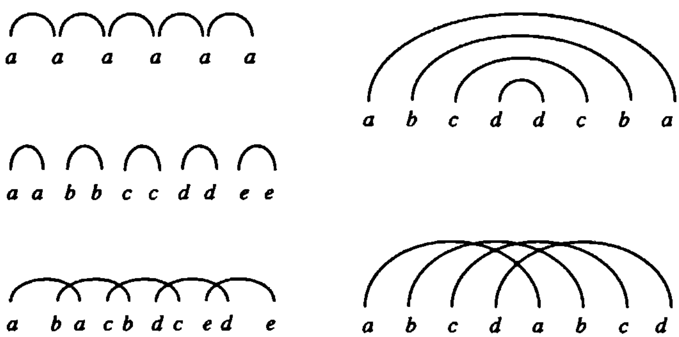


Figure 6. Five characteristic visualizations of holographic regularity. In the five prototypical symbol series, each identity relationship between two symbols is visualized by an arc. For each series, the set of arcs shows a regular ordering. The holographic property of this ordering is reflected by the fact that the first or the last arc in each set can be removed without distorting the regular ordering in the set of arcs.

Finally, ignoring syntactical variations in the definitions of specific coding rules (since such variations are irrelevant with respect to the meaning of coding rules), one can prove that each of the 20 cases of holographic regularity can be described by precisely 4 different coding rules. So, the final result is that only precisely 80 so-called holographic coding rules exist. Among these 80 coding rules are the ISA-rules as employed in the structural information model. Figure 7 shows, for the Iteration rule, a scheme that typically holds for any holographic coding rule.

Now, if holographic regularity is accepted as being relevant and if 80 holographic coding rules exist, one might wonder why the structural information model employs only the ISA-rules. Well, the answer lies in the fact that, above, only the intrinsic character of regularity has been dealt with. So far, nothing has been said about the way cases of regularity can be related hierarchically. The latter aspect is, in the formalization, specified by the formal notion of transparent hierarchy. This notion is, even more than the notion of holographic regularity, relevant with respect to the complexity metric to be proposed, and will be discussed next.

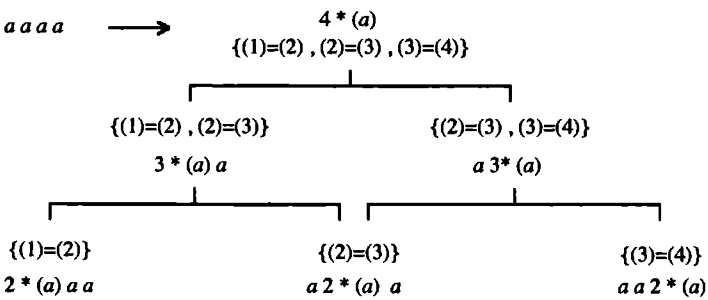


Figure 7. The holographic Iteration rule The series 'aaaa' can be encoded into the I-form shown at the top, expressing the identity structure (chain) consisting of three identities. For each substructure (subchain) of this identity structure, an I-form exists such that it expresses that substructure. This indicates that the Iteration rule is a holographic coding rule.

3.2 *Transparent hierarchy*

Metaphorically, transparent hierarchy may be illustrated by the hierarchical structure of an industrial organization. In such an organization, the position of the manager may rely on that structure, but the manager can also be approached independently of the other employees. The analogue in terms of symbol series may be illustrated as follows.

In encoding models like the structural information model, the coding rules yield hierarchical descriptions of regularity in a symbol series. For instance, as we saw before, the series 'ababbaba' can be encoded into the S-form 'S[(a)(b)(a)(b)]'. In this S-form, the S-argument '(a)(b)(a)(b)' is said to represent a higher hierarchical level and can be encoded into the I-form '2*((a)(b))'. The latter code can be nested in the S-form, yielding the hierarchical code 'S[2*((a)(b))]'. Note that the S-form describes regularity in the symbol series, but that the I-form describes regularity in the S-argument at a higher hierarchical level. So, one might wonder what the meaning of the I-form is with respect to the description of regularity in the symbol series 'ababbaba'. Now, observe that the I-form '2*((a)(b))' in the S-argument '(a)(b)(a)(b)' describes a kind of regularity (a repetition of two times something) that is also described by the I-form '2*(ab)' in the subseries 'abab' of the symbol series 'ababbaba'. This example illustrates a general characteristic of the S-rule, namely that any kind of regularity in the argument of an S-form corresponds unambiguously to the same kind of regularity in the symbol series. So, in an almost visual sense, any S-form is "transparent", i.e. regularity in the symbol series can be "seen through" the S-form. And indeed, because of this general characteristic, the S-rule is called a transparent coding rule. For the example above, this implies that the hierarchical code 'S[2*((a)(b))]' can be seen as indicating that the S-form 'S[(a)(b)(a)(b)]' and the I-form '2*(ab)' can be related hierarchically. Inversely, this implies that, instead of the I-form '2*((a)(b))' in the S-argument, one could just as well consider the I-form '2*(ab)' in the symbol series. Thus, analogous to the manager in the metaphor, the higher level I-form can be considered independently of the lower-level S-form. Moreover, note that, in the example above, the I-form '2*(ab)' induces the chunking '(ab)(ab)' in the subseries 'abab' of the symbol series 'ababbaba'. This chunking can be superimposed on the chunking '(a)(b)(a)(b)(b)(a)(b)(a)' as induced by the S-form in the symbol series, yielding the hierarchical chunking '((a)(b)) ((a)(b)) (b)(a)(b)(a)' in the symbol series (see Figure 8). Such a hierarchical chunking can be assigned unambiguously to any hierarchical code obtained by means of transparent coding rules and is, therefore, called a transparent hierarchy. So, a hierarchical code obtained by means of transparent coding rules indicates how different cases of regularity in a symbol series can be related hierarchically, and the resulting hierarchical code induces a hierarchical chunking in the symbol series.

	LEVEL 1:	*a b*	*a b*	*b a*	*b a*
S[(*a*)(*b*)(*a*)(*b*)]	↓				
	LEVEL 2:	(*a*)(*b*)	(*a*)(*b*)	(*b*)(*a*)	(*b*)(*a*)
S[2*((*a*)(*b*))]	↓				
	LEVEL 3:	((*a*)(*b*))	((*a*)(*b*))	(*b*)(*a*)	(*b*)(*a*)

Figure 8. The transparent Symmetry rule. The S-form 'S[(a)(b)(a)(b)]' induces a chunking in the level 1 symbol series, represented by the level 2 series. The I-form '2*((a)(b))' in the S-argument corresponds unambiguously to the I-form '2*(ab)' in the level 1 series, inducing the chunking '(ab)(ab)' which can be superimposed on the level 2 series, and leading to the hierarchical chunking represented at level 3.

From the example just given, one may get the impression that, for coding rules, transparency is only a plausible requirement and may even be rather trivial. This may be the case for the S-rule but, for coding rules in general, transparency is far from trivial. This may be illustrated by means of the so-called M-rule which is one of the 80 holographic coding rules mentioned earlier, and is defined as follows:

$$k_1x_1k_1 \quad k_2x_2k_2 \; \ldots \; k_nx_nk_n \rightarrow M[(k_1)(k_2)\ldots(k_n),(x_1)(x_2)\ldots(x_n)].$$

The M-rule can be applied to express that a series contains successive subseries which each begin and end identically. Now, consider the symbol series 'ara bsb aya bzb' which, by means of the M-rule, can be encoded into the following M-form: 'M[(a)(b)(a)(b),(r)(s)(y)(z)]'. The first argument of this M-form, '(a)(b)(a)(b)', can be encoded into the I-form '2*((a)(b))'. However, this I-form describes, in the first M-argument, a kind of regularity (a repetition of two times something, i.e. two successive identical subseries) which does not occur in the symbol series itself. Therefore, the M-rule is not a transparent coding rule. In fact, one finds in this way that only 9 of the 80 holographic coding rules are transparent coding rules, among which the ISA-rules as employed in the structural information model.

Since the transparency of the ISA-rules is important with respect to the new complexity metric, we will now go into the transparency of the I-rule and the A-rule in some detail. The I-rule is transparent "by default", since the I-argument of an I-form consists of only one chunk so that, at the higher hierarchical level, no regularity can be described. The transparency of the A-rule, however, is not that trivial. We saw that the A-rule can be applied to express that a series contains successive subseries which either all begin or all end identically, as follows:

$$kx_1 \quad kx_2 \; \ldots \; kx_n \rightarrow <(k)>/<(x_1)(x_2)\ldots(x_n)>$$

$$x_1k \quad x_2k \; \ldots \; x_nk \rightarrow <(x_1)(x_2)\ldots(x_n)>/<(k)>.$$

Clearly, the two cases are very similar, and we will discuss only the transparency for the first case. Suppose the symbol series 'kxkykykz' is encoded into the A-form '<(k)>/<(x)(y)(y)(z)>'. Then, the subseries '(y)(y)' in the A-argument can be encoded into the I-form '2*((y))', yielding the hierarchical code '<(k)>/<(x) 2*((y)) (z)>'. Now, observe that the I-form '2*((y))' in the A-argument does not correspond to an I-form '2*(y)' in the symbol series 'kxkykykz'. Yet the regularity described by the I-form in the A-argument does correspond unambiguously to the same kind of regularity in the symbol series. That is, the I-form in the A-argument corresponds unambiguously to the I-form '2*(ky)' in the symbol series. Note that, in the latter I-form, the I-argument '(ky)' corresponds to an A-pair cluster as discussed before. Similarly, in general (see definition above), for an A-form '<(k)>/<(x_1)...(x_n)>', any regularity in the argument '(x_1)(x_2)...(x_n)' corresponds unambiguously to the same kind of regularity in the series '(kx_1)(kx_2)...(kx_n)' consisting of A-pair clusters. Clearly, any kind of regularity in this cluster series corresponds unambiguously to the same kind of regularity in the symbol series 'kx_1 kx_2 ... kx_n', thus showing that the A-rule is indeed a transparent coding rule. Furthermore, in the example above, the A-form '<(k)>/<(x)(y)(y)(z)>' induces the chunking '(k)(x)(k)(y)(k)(y)(k)(z)' in the symbol series, while the I-form '2*(ky)' induces the chunking '(ky)(ky)' in the subseries 'kyky' of the symbol series. Clearly, the latter chunking can be superimposed on the former chunking, yielding the hierarchical chunking '(k)(x) ((k)(y)) ((k)(y)) (k)(z)' (see also Figure 9). So, in order to understand the hierarchical character of the A-rule, one should replace each chunk in the A-argument by the related A-pair, in order to obtain the chunking at the higher hierarchical level.

	LEVEL 1:	*k x*	*k y*	*k x*
<(k)>/<(x)(y)(x)>	↓			
	LEVEL 2:	(*k*)(*x*)	(*k*)(*y*)	(*k*)(*x*)
<(k)>/<S[((x)),((y))]>	↓			
	LEVEL 3:	((*k*)(*x*))	((*k*)(*y*))	((*k*)(*x*))

Figure 9. The transparent Alternation rule. The A-form '<(k)>/<(x)(y)(x)>' induces a chunking in the level 1 series, represented by the level 2 series. The S-form 'S[((x)),((y))]' in the second argument of the A-form corresponds unambiguously to the S-form 'S[(kx),(ky)]' in the level 1 series, inducing the chunking '(kx)(ky)(kx)' which can be superimposed on the level 2 series, leading to the hierarchical chunking represented at level 3.

3.3 *Implications of formal regularity*

We have given an overview of the formalization of the intuitive concept of regularity, specified by the formal notions of holographic regularity and transparent hierarchy. Holographic regularity applies to the intrinsic character of regularity, and reflects the fact that, for example, an arbitrary repetition belongs to the set of all repetitions. Transparent hierarchy applies to the way different cases of regularity can be related hierarchically, and implies that the hierarchical character of codes is not just a syntactical artifact of the coding language, but a psychologically meaningful aspect of the description of regularity. The result of the formalization is that only 80 coding rules are such that they describe holographic regularity, and that only 9 of these 80 coding rules are such that they describe transparent hierarchy too. Among these 9 transparent holographic coding rules are the ISA-rules as employed in the structural information model. Actually, the other transparent holographic coding rules are superfluous in the sense that they describe only identities that can also be described by the ISA-rules, while the ISA-rules can describe other identities as well. This implies that, according to the formalization, a set of appropriate coding rules may consist of just the ISA-rules. This result as such is not very surprising, since the kinds of regularity as described by the ISA-rules are widely accepted as being relevant in perception and have been emphasized by various scientists (e.g. Wertheimer, 1923; Koffka, 1935; Palmer, 1977). The way this result has been obtained is what matters here, because the ISA-rules now have a unique formal status which is psychologically relevant. The psychological plausibility is supported by several further implications of the formalization, as we will argue next. If holographic coding rules are used to extract pattern information (regularity) from a symbol series that represents a pattern, then the extraction is very easy, i.e. the pattern information to be extracted is very accessible. This may be illustrated by the holographic I-rule, for which I-forms can be constructed in a simple stepwise fashion, starting with any single identity and with each step adding just one identity, e.g. as follows (see also Figure 7):

aaaa $\rightarrow$ 2*(a) aa $\rightarrow$ 3*(a) a $\rightarrow$ 4*(a).

So, for the I-forms, the construction proceeds from one I-form towards another I-form, each step enlarging the expressed identity structure by one identity. Clearly, this is possible because of the holographic property that any iteration belongs to the collection of all iterations. Thus, complex combinations of identities do not have to be matched, since the construction involves "atomic" steps of one identity at a time.

Maybe even more than the notion of holographic regularity, the notion of transparent hierarchy results in the accessibility of pattern information as contained in a symbol series. As we saw before, the transparency of coding rules implies that regularity at a higher hierarchical level in a code of the series corresponds unambiguously to the same kind of regularity in the series itself. Since the classification and the organization of the series is based on the described regularity, the transparency implies that higher cognitive levels will deal with (or have access to) basic pattern information itself. That is, the information that is considered to be passed on to higher cognitive levels is not, as with an artifact of the employed model, based on just regularity at a higher hierarchical level in a code, but on regularity in the pattern. Moreover, the notion of transparent hierarchy yields the possibility of a largely parallel encoding process, as follows. As we saw before, the hierarchical code 'S[2*((a)(b))]' can be seen as indicating that the S-form 'S[(a)(b)(a)(b)]' and the I-form '2*(ab)' can be related hierarchically. This implies that the I-form and the S-form can be constructed independently of each other, and then tested on hierarchical compatibility. This shows that, in general, all single ISA-forms in a symbol series can be constructed in parallel after which they can be tested, in parallel too, in pairs for hierarchical compatibility. Thus, on the one hand, the encoding may result in a hierarchy consisting of sequentially ordered hierarchical levels but, on the other hand, this hierarchy does not have to be established in a strictly sequential way. This illustrates that, in our view, the notion of hierarchy should not be based on some process model as such, as in, for example, the so-called hierarchical sequential search model of Simon and Feigenbaum (1964), or as in other so-called top-down models that involve reasoning or unconscious inferences (Von Helmholtz, 1867; Neisser, 1966; Gregory, 1972; Rock, 1983). Nor should hierarchy be seen, as suggested in Buffart (1987), as a property of a single pattern representation in which several different hierarchical levels can be distinguished by decomposing that representation (see also Van der Helm, 1988). On the contrary, hierarchy should rather be seen as a relation between several different representations of the same pattern. That is, several different ISA-forms, obtained in parallel, may be related hierarchically in order to compose a hierarchy consisting of several different hierarchical levels. In the latter sense, the notion of hierarchy agrees with a bottom-up extraction of gradually more structured information. That is, starting from the single identities in a "raw" pattern registration, regularity is described first and then different kinds of regularity are related hierarchically, resulting in a classification and an organization which can be "embedded" in stored knowledge structures.

Another implication of the formalization is related to the problem that the minimum principle seems to require an unrealistic search for simplest codes since, for an arbitrary symbol series, the number of possible codes is combinatorially explosive (cf. Hatfield & Epstein, 1985). This problem does not depend on the exact complexity metric that is used. For instance, if a series can be encoded entirely into one S-form (or A-form) then, in general, the series can be encoded entirely into an exponential number of S-forms (or A-forms). Because of the notions of holographic regularity and transparent hierarchy, however, these S-forms (or A-forms) can all be stored and encoded simultaneously, as if it were just one S-form (or A-form). Thus, the search for the simplest S-form (or A-form) becomes realistic, since it does not involve an explosive amount of storage space or processing time. For detailed information on this problem and its solution, we refer to Van der Helm & Leeuwenberg (1986, 1991) and Van der Helm (1988).

The discussion in this subsection shows that the formalization of regularity not only provides a psychological basis for the choice of appropriate coding rules, but also has further implications that are psychologically relevant. The implication that is most relevant in the present paper is the fact that the formalization paves the way for a new complexity metric. This implication will be discussed next.

4 The new complexity metric

In this section, we will discuss and evaluate complexity metrics, on the basis of the analysis in the previous section. First, in order to clarify the need for a new metric, we consider three metrics that have been used more or less frequently in earlier research on the structural information model. Then, we introduce the new metric.

4.1 I_{old}-load

In many studies concerning the structural information model, the complexity of a code has been measured by means of the I_{old}-load (Leeuwenberg, 1971). This load was meant to reflect the amount of memory space needed to represent a code, i.e. the preferred pattern interpretation is assumed to be reflected by the code that requires a minimum of storage space. Therefore, an assumption has been made with respect to the relation between the syntactical components in a code and the memory space needed to represent the code, as follows. First, the encoding of a series yields a reduction of the series into a code, so that not all of the pattern symbols in the series, but only those in the code, need to be represented in memory. Second, the means of establishing the reduction have to be taken into account as well. These means consist of the ISA-forms, and are taken into account as follows. For decoding a stored I-form like '5*(ab)' into the series 'ababababab', the numeric value '5' has to be known and is, therefore, assumed to be represented in just as much memory space as each of the two pattern symbols, so that this I-form requires three units of memory space. In decoding a stored S-form like 'S[(a)(b)(c)]' into the series 'abccba', the S-argument has to be reversed in order to produce the second half of the series; this reversal operation is assumed to be represented in, again, just as much memory space as each of the three pattern symbols, so that this S-form requires four units of memory space. For decoding a stored A-form like '<(a)>/<(r)(s)(t)>' into the series 'arasat', the number of times that the part 'a' has to be repeated does not have to be stored since this number is implicitly given by the number of elements in the A-argument '(r)(s)(t)'; therefore, the storage of this A-form requires only four units of memory space, i.e. only for the four pattern symbols. So, for an arbitrary code, one has to count the pattern symbols, the I-forms, and the S-forms in the code to determine the I_{old}-load of the code, i.e. the complexity of the code in terms of storage space. The structural information model has gained empirical support by using the I_{old}-load as a complexity metric. However, the I_{old}-load gives rise to several conceptual problems. First, the pattern symbols, the numeric value in an I-form, and the reversal operation for an S-form, are given equal value but are in fact incomparable entities, at least very different entities. For example, why not assign the value of the numeric value and of the reversal operation as being equal to two or more pattern symbols? Second, the reversal operation for an S-form is counted, but not the iteration operation for an I-form, nor the alternation operation for an A-form. These conceptual problems indicate that the I_{old}-load is based on a dubious, and in our view unacceptable, assumption concerning the relation between syntactical components in a code and the memory space needed to represent the code. That is, in our view (see also Hatfield & Epstein, 1985), this assumption depends too much on artifacts of the encoding language. Moreover, in our view, the semantical implication of a code (i.e. an interpretation) should not be judged on the basis of the required memory space but, psychologically more meaningful, on the basis of the semantical content of the code (i.e. the description of regularity). The conceptual problems with respect to the I_{old}-load have been recognized in research concerning the structural information model; the following complexity metric was devised to overcome these problems.

4.2 *P-load*

In order to determine the P-load of a code, one simply counts the number of pattern symbols in that code (cf. Collard & Buffart, 1983). For instance, for the code '3*(ab)', the value of the P-load is P=2, because it contains only two pattern symbols, 'a' and 'b'. This metric implies a judgement of the resulting classification, as follows. For instance, as we saw in the second section, if the series 'aaaaaa' is encoded into the I-form '3*(aa)', for which P=2, then the series is considered to be classified into the class of series that can be represented by, for example, the series 'yzyzyz'. Occasionally, such a class representative has been called an abstract code (cf. Collard & Buffart, 1983). Now note that, in the example above, the I-form '3*(aa)' described regularity in the symbol series 'aaaaaa' by expressing the identity of elements contained in the abstract code 'yzyzyz'. Therefore, the residual nonidentity of elements in the abstract code can be regarded as the irregularity in the symbol series (at least, according to the I-form). Now, the P-load of a code equals the number of different elements in the corresponding abstract code and, therefore, implies a judgement of the resulting classification by measuring irregularity: the more different elements, the more irregularity, the more complex.

So, the P-load applies to the output of the encoding model, i.e. does not depend on artifacts of the encoding language. Therefore, conceptually, the P-load seems better than the I_{old}-load. Yet, the P-load has not been used frequently, because it yields worse predictions than the I_{old}-load. A possible explanation for this leads, as follows, to a third metric.

4.3 *I_A-load*

On the one hand, the P-load accounts only for the resulting classification, not for the resulting organization. Since both the classification and the organization are part of the output, one could say that the P-load is incomplete so that the P-load still gives rise to a conceptual problem. On the other hand, the I_{old}-load can be seen as accounting for not only the resulting classification but also, although only to some extent, for the resulting organization, as follows. First, note that the I_{old}-load of a code equals the P-load of the code plus the number of I-forms and S-forms in the code. That is, the I_{old}-load can be seen as accounting for the classification in the same way as does the P-load. Now suppose that, instead of only the I-forms and S-forms, the A-forms in a code are also counted. Let us call this adapted metric the I_A-load. Now, recall that the argument of an ISA-form represents a higher hierarchical level (in the code as well as, as we saw before, in the resulting organization). That is, each ISA-form in a code yields a transition to a higher hierarchical level. Thus, counting all ISA-forms in a code corresponds to counting all hierarchical levels. In this way, the I_A-load can be seen as taking into account the resulting organization. So, similarly, the I_{old}-load can be said to account for the resulting organization (though only to some extent since the A-forms are not counted), which might explain why it yields better predictions than does the P-load. For the same reason, we expect (and hypothesize in the experiment to be discussed) that the I_A-load, which also counts the A-forms, should yield better predictions than the I_{old}-load.

However, this way of accounting for the resulting organization gives rise, as before, to a conceptual problem. Namely, hierarchical levels and pattern symbols are valued equally but are, in fact, incomparable entities. That is, whereas the number of pattern symbols refers directly to something (namely, irregularity) that is present in a symbol series, the number of hierarchical levels refers only to the presence of those levels as such, i.e. not to something that is present at those levels. The new complexity metric does not show such a conceptual problem, as we will see next.

4.4 *I_{new}-load*

To a large extent, the new complexity metric, the I_{new}-load, is based on the concept of transparent hierarchy, as discussed before. In the present study, we have seen that if a symbol series is encoded by means of the ISA-rules, then the resulting code unambiguously induces a transparent hierarchy, i.e. a hierarchical chunking, in the symbol series (see Figures 8 and 9). Now, imposing the same hierarchical chunking on the corresponding abstract code (as defined when discussing the P-load), yields an organized class representative which reflects both the resulting classification and the resulting organization of the symbol series. For instance, if the symbol series 'abcabcab' is encoded into the S-form 'S[(ab)(c),(ab)]', then the classification is represented by the abstract code 'xztpqtxz', while the organization is represented by the chunk series '(ab)(c)(ab)(c)(ab)'. Imposing this same chunking on the abstract code yields the expression '(xz)(t)(pq)(t)(xz)'. Such an expression will be said to represent an abstract chunking. Note that, in general, such an abstract chunking exists only for codes obtained by means of transparent coding rules.

Now, in the new complexity metric, the I_{new}-load, all the different elements over all the hierarchical levels in such an abstract chunking are counted. For instance, for the S-form above, I_{new}=7, since the abstract chunking contains the following seven different elements: 'x', 'z', '(xz)', 't', 'p', 'q' and '(pq)'. Note that the lower-level element 't' is not different from the higher-level element '(t)' since, in this case, the parentheses merely indicate a chunk that equals one symbol. That is, in addition to the different single symbols, only the different chunks consisting of at least two symbols or chunks are counted. This may be illustrated by two further examples. In Figure 8, we saw that the encoding of the symbol series 'ababbaba' into the code 'S[2*((a)(b))]' yields a transparent hierarchy which is represented by the expression '((a)(b)) ((a)(b)) (b)(a) (b)(a)'. Since the code characterizes all the identity of elements in the symbol series, the latter expression also represents the abstract chunking. This abstract chunking contains three different elements, namely: 'a', 'b', and '((a)(b))', so that the code has an I_{new}-load of I_{new}=3. Furthermore, in Figure 9, we saw that the encoding of the symbol series 'kxkykx' into the code '<(k)>/<S[((x)),((y))]>' yields a transparent hierarchy which is represented by the expression '((k)(x)) ((k)(y)) ((k)(x))'. Again, the code characterizes all the identity of elements in the symbol series, so that the latter expression also represents the abstract chunking. This abstract chunking contains five different elements, namely: 'k', 'x', '((k)(x))', 'y', and '((k)(y))', so that the code has an I_{new}-load of I_{new}=5.

Now that we have introduced the I_{new}-load, we first of all want to emphasize that this complexity metric does not depend on artifacts of the coding language, because it is based solely on the output, i.e. on the classification and organization. Therefore, it does not show the conceptual problems connected with the I_{old}-load. A better account is now given of the hierarchical structure by counting not just hierarchical levels but the different elements at those levels. Counting the different elements at some level corresponds, as we saw when discussing the P-load, to measuring the irregularity at that level. In other words, the I_{new}-load, can be said to account for the hierarchical structure by quantifying its contribution to pattern complexity in terms of the irregularity at higher levels. This way, the I_{new}-load can be said to measure pattern complexity by adding irregularity and hierarchy.

In section 5, we will discuss an experiment that has been designed to test the new complexity metric by considering the dominant segmentation in the perceptual organization as predicted on the basis of the simplest code (as discussed before). We argued that one has to take notice of not only the chunking but also the clustering as part of the perceptual organization of a pattern. That is, for instance, the series 'abab' is chunked into '(ab)(ab)' in order to describe the iteration regularity by means of the I-form '2*(ab)', which implies that the entire series 'abab' is clustered into one regularity structure which is represented by the cluster '(abab)'. Note that clustering is not taken into account in the new complexity metric. Whereas chunks are needed to construct ISA-forms, clusters are "only" a consequence of ISA-forms. Therefore, clustering may be relevant in experimental settings but is not relevant with respect to the complexity of ISA-forms.

5 Experiment

The following experiment has been designed to test the structural information model using the new metric of complexity, i.e. the I_{new}-load as discussed in the previous section. This test comprises a comparison, with respect to preferred pattern segmentations, between the new metric and the other metrics discussed in section 4, i.e.

the P-load, the I_{old}-load, and the I_A-load. Each pattern, as used in the experiment, is a patterned sequence in which the elements are drawn from one of three different sets of graphic symbols (see Figures 10 and 11). For each pattern, subjects were asked to indicate the preferred pattern segmentation. In each trial, subjects were forced to choose out of two given pattern segmentations. Each of the two segmentations was the dominant segmentation in the perceptual organization as induced by a code obtained by means of the ISA-rules. So, given one of the complexity metrics, one could check in each trial which of the two codes was the simpler one and whether or not that code indeed induces the preferred segmentation. Thus, one can investigate which of the complexity metrics performs best. Patterned sequences were chosen because a straightforward semantic mapping can be assumed between a (serial) pattern code and the pattern. That is, still existing unclarities with respect to the semantic mapping, e.g. for (nonserial) two-dimensional patterns, or (serial) auditory patterns, are excluded. The specific stimuli were selected such that the various metrics mostly yield different predictions (except for the P-load which, as will be clear, is used as a sort of "baseline").

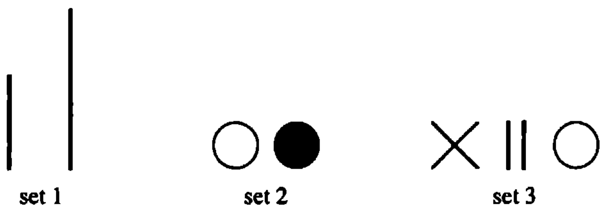


Figure 10. The three sets of graphic symbols used in the experiment. To construct a stimulus, graphic symbols from one set are drawn and composed into a patterned sequence. The graphic symbols within a set are very distinctive phenomenally (short versus long; white versus black; cross versus parallel versus circular), so that they can be considered as basic pattern elements.

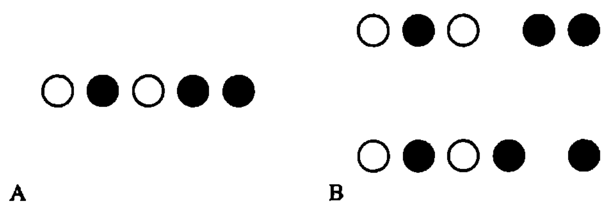


Figure 11. A target (A) and response alternatives (B) as used in the experiment. The patterned sequence at the left was constructed by assigning graphic symbols from set 2 in Figure 10 to the symbols in the symbol series 'ababb'. In the segmentations shown in (B), a large space between two graphic symbols indicates a border between two segments. Subjects were asked to indicate which of the two segmentations they prefer as partitioning of the target into coherent parts.

5.1 *Hypothesis*

In line with the minimum principle we predict that the simpler the code of a pattern, the greater the preference for the segmentation induced by that code. Now, for some complexity metric M, let G(M) be the goodness of M, i.e. the amount of preferred pattern segmentations that M predicts correctly. Then, on the basis of the theoretical analysis in the previous sections, we hypothesize that:

$$G(\text{P-load}) < G(I_{old}\text{-load}) < G(I_A\text{-load}) < G(I_{new}\text{-load}).$$

A brief explanation of this is as follows: in the previous section, we argued that the complexity of a pattern code is constituted by the irregularity and the hierarchy as represented in that code. Schematically, the four metrics count the following code components:

P-load	: pattern symbols
I_{old}-load	: pattern symbols plus IS-forms
I_A-load	: pattern symbols plus ISA-forms
I_{new}-load	: pattern symbols plus chunks

By counting the pattern symbols, the four metrics all account in the same way for irregularity, so that differences between the metrics have to be sought in the way of accounting for hierarchy. According to the theoretical analysis and the hypothesis, the successive metrics account for hierarchy in a better way: the P-load does not take hierarchy into account; the I_{old}-load counts some of the higher hierarchical levels in a code; the I_A-load counts all higher hierarchical levels in a code; and the I_{new}-load accounts for hierarchy in terms of irregularity at higher hierarchical levels. Note that the main issue will be to contrast the I_{new}-load with the I_{old}-load, the most frequently used metric in earlier empirical research on the structural information model. The less frequently used P-load and I_A-load are considered mainly to obtain a more detailed view on the adequateness of the theoretical analysis in the previous sections.

5.2 *Method*

5.2.1 *Subjects*

Thirty-one undergraduates received course credit to participate in the experiment.

5.2.2 *Materials*

To construct the patterns for the experiment, i.e. the patterned sequences of graphic symbols, three different sets of graphic symbols were used (see Figure 10). For each pattern, graphic symbols were drawn from one set of such symbols to construct a sequence (see Figure 11A). In each set, the graphic symbols are "semantically independent", i.e. are very distinct phenomenally (set 1: short versus long; set 2: white versus black; set 3: cross versus parallel versus circular). This ensures that subsequent graphic symbols in a pattern will not be grouped together because of the "visual distance" (cf. Tversky & Gati, 1982), such as for a regular increase of grey-value, or because they constitute, for example, a complementary pair of parentheses. This, together with the symmetry in each graphic symbol, implies that the symbols can be considered as "primitives", i.e. as basic pattern elements which are not sensitive to biases that are irrelevant with respect to the goal of this experiment. This ensures that a straightforward semantic mapping can be assumed between such a patterned sequence and a symbol series as used in the structural information model. For instance, the pattern at in Figure 11A can be represented by the symbol series 'ababb'. This symbol series 'ababb' can be encoded using the ISA-rules, to yield the code 'S[(a),(b)] 2*(b)' or the code '2*(ab) b'. The former code is the simplest code according to the I_{new}-load, implying that '(aba)(bb)' is the dominant segmentation, whereas the latter code is the simplest code according to the I_{old}-load, and implies that '(abab)(b)' is the dominant segmentation. These two segmentations of the symbol series can be mapped straightforwardly onto two segmentations of the patterned sequence of graphic symbols (see Figure 11B, in which the large space between two of the graphic symbols stands for the border between the two segments). Thus, each stimulus can be constructed from a patterned sequence of graphic symbols (the target) and two relevant segmentations (response alternatives) out of which subjects can choose the preferred segmentation. These preferences can be checked to determine which complexity metric correctly predict them.

The total stimulus set consisted of 240 stimuli, derived from 40 different symbol series like the above-mentioned 'ababb' (see also below). Among these 40 series, 24 series contained 2 different symbols, and 16 series contained 3 different symbols. The length of the series varied from 5 up to 18 symbols. For each of the 40 series, three different segmentations were considered. For example, for 'ababb', the two segmentations mentioned above, plus the segmentation '(ab)(abb)' as induced by the code '<(a)>/<(b)(2*(b))>' were considered. Out of these three segmentations, the three different pairs of segmentations were each used in a stimulus. This yields 40*3=120 "symbolic" stimuli, i.e. stimuli in terms of symbols as used in the structural information model and not yet in terms of graphic symbols as used in the experiment. Furthermore, from each of the 120 "symbolic" stimuli, one additional "symbolic" stimulus was derived by reversing the order of the symbols both in the symbol series and in the two segmentations, e.g. for the series 'ababb', the reversal of the series is 'bbaba', and the reversal of the segmentation '(ab)(abb)' is '(bba)(ba)'. Note that the latter segmentation is induced by the "reversed" A-form '<(2*(b))(b)>/<(a)>', and that any code can be reversed in a similar way. Thus, one gets a total of 120*2=240 symbolic stimuli.

During the experiment, each of the 240 symbolic stimuli was assigned randomly to one of the three graphic symbol sets. (Clearly, symbolic stimuli containing three different symbols can only be assigned to set 3 in Figure 10.) Then, each of the different symbols in the symbolic stimulus was assigned randomly to one of the graphic symbols in that set. Thus, one obtains the actual stimulus set consisting of 240 stimuli. In order to cancel out any residual bias with respect to the graphic symbols, this random transformation of the symbolic stimuli into real stimuli was performed for each subject individually. The transformation was performed by a computer program that was developed to run the experiment and to present the stimuli on a monitor.

For selecting the 40 symbol series from which the 240 stimuli were derived, and for selecting the three segmentations for each of the 40 series, three criteria were used:
(i) For each symbol series, the three codes that induce the three segmentations should have the same P-load but different complexities according to each of the other three metrics such that, for each of these three metrics, the simplest code is included. That is, the P-load was used as a baseline because the P-load takes irregularity into account in the same way as do the other metrics but does not account for hierarchy, whereas the other three metrics precisely differ in how they take into account hierarchy. In this way, the experimental results can be related to the differences between the metrics.
(ii) The 40 symbol series should be balanced with respect to the length of a subseries that is covered by a specific ISA-rule. For instance, the series 'ababb' shows an iteration of the subseries 'ab' and a partly overlapping iteration of subseries 'b'. The preference for one of these iterations may depend on how prominent such an iteration is in a series. Therefore, also included were series like 'abababab' and 'ababbbb', in which one of the iterations is more redundantly present.
(iii) For each of the 40 symbol series, each ISA-rule should be used in at least one of the three codes, so that the results indeed apply to the entire encoding model.

These criteria are hard to meet simultaneously; thus they are met to a large extent for the entire stimulus set but not for every stimulus. This holds in particular for the requirement for different complexities for each of the three codes, as given in the first criterion. That is, in the set of 240 stimuli two subsets can be distinguished for each metric. One subset contains the stimuli in which the two segmentations are induced by equally complex codes so that the metric predicts ambiguity, i.e. no preference for one of the two segmentations. The other subset contains the stimuli for which the metric predicts nonambiguity, i.e. a preference for one of the two segmentations since the two codes differ with respect to complexity. In the analysis of the results, these two subsets are considered separately. In Figure 12, the sizes of the two subsets are shown for each of the metrics, except for the P-load. As mentioned above, the P-load is used as the "baseline", and predicts ambiguity for almost all stimuli. Furthermore, the P-load was already known to be inadequate, so that the experimental results are not very interesting with respect to the P-load (unless, of course, the results showed that most of the stimuli are indeed ambiguous but, as will be clear, this is not the case). Therefore, the P-load is not only omitted in Figure 12 but also in the analysis of the results. To conclude this subsection on stimulus selection, some examples of the symbol series, as used in the experiment, are given in Table 1. Each symbol series is encoded in three different ways. Each pair out of the three segmentations for one series represents the response alternatives for the stimulus.

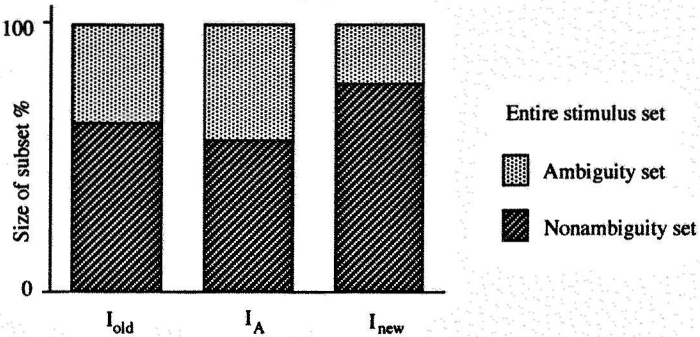


Figure 12. For each complexity metric, the sizes of the two subsets (expressed as a percentage of the total 240 stimuli) that contain the stimuli for which that metric predicts nonambiguity (i.e. preference for one of the two response alternatives) and ambiguity (i.e. no preference), respectively. In the analysis of the results, these subsets are dealt with separately.

Series	Code	Segmentation	P	I_{old}	I_A	I_{new}
ababb	2x(ab)b	(abab)(b)	3	4	4	4
	S[(a),(b)]2x(b)	(aba)(bb)	3	5	5	3
	<(a)>/<(b)(2x(b))	(ab)(abb)	3	4	5	4
aabaabb	2x(2x(a)b)b	(aabaab)(b)	3	5	5	4
	S[2x((a)),(b)]2x(b)	(aabaa)(bb)	3	6	6	3
	<(2x(a))>/<(b)(2x(b))>	(aab)(aabb)	3	5	6	5
abcabcc	2x(abc)c	(abcabc)(c)	4	5	5	5
	S[(ab),(c)]2x(c)	(abcab)(cc)	4	6	6	5
	<(ab)>/<(c)(2x(c))>	(abc)(abcc)	4	5	6	6

Table 1. Three examples of symbol series used in the experiment. Each pair out of the three segmentations for one series represents the response alternatives. The values for the four metrics are given.

5.3 *Procedure*

All subjects were tested individually. As the total duration of the experiment was about 1.5 h, there was a break halfway through the experiment. All subjects were given the same instructions, projected onto a monitor. Each stimulus was presented as follows. First, only the target (a patterned sequence of graphic symbols) was presented in the middle of the left-hand side of the screen. After 7 s, the response alternatives (two segmentations of the target) were presented in addition, at the right-hand side of the screen, one in the upper half and one in the lower half of the screen (as in Figure 11). The task was "to decide how you would partition the pattern into coherent parts" (during the 7 s), and then "to select, from the two partitionings, the partitioning that resembles your own partitioning most closely". Pilot investigations showed that subjects had a clear preference within a period of 7 s. Subjects responded by pressing one of two buttons on the table in front of them, the buttons corresponding in position to the positions of the response alternatives on the screen (top versus bottom).

First, 10 trials were presented so as to get acquainted with the task, then the actual experiment began by the 240 stimuli being presented in random order. As mentioned before, the random transformation of the 240 symbolic stimuli into real stimuli was performed for each subject individually. The position of each response alternative (top or bottom) was randomized too. In the response alternatives, the larger spaces between the segments were made such that the visual angle for both response alternatives was always equal (as in Figure 11), independent of the number of segments. The computer registered not only each response, but also each response time, this being the time between the onset of the response alternatives and pressing the button.

5.4 *Results*

Each of the 31 subjects performed all 240 trials, so that the total number of trials was 31*240=7440 trials. As mentioned before, the P-load is not considered and, for each of the other three metrics, the nonambiguity set and the ambiguity set are considered separately (see Figure 12). Since the subjects performed a forced-choice task, the metrics cannot be tested for correct predictions for stimuli in the respective ambiguity sets. Only if, experimentally, stimuli in an ambiguity set appear to be significantly nonambiguous, can the respective metric be said to have predicted falsely. The latter cases will be dealt with together with the false predictions for stimuli in the nonambiguity sets. First, the correct and false predictions for stimuli in only the non-ambiguity sets are considered.

Figure 13 shows, for each of the three nonambiguity sets, a histogram of the raw data. In each histogram, the bars represent disjunct stimulus subsets, together constituting the entire nonambiguity set. The height of a bar represents the size of the subset, and the position on the horizontal axis represents the number of subjects for which the respective metric correctly predicted the responses to the stimuli in that

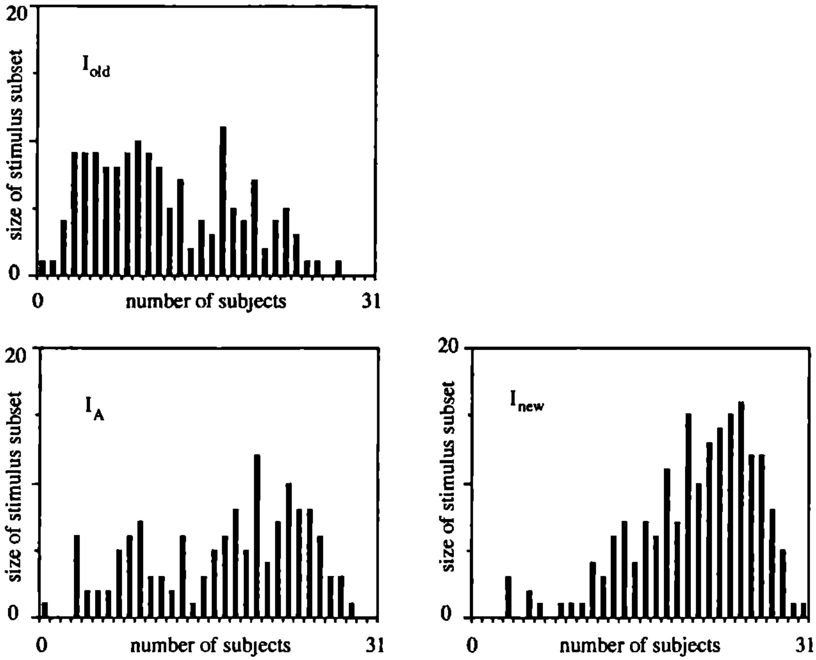


Figure 13. Histograms of the raw data for each metric on its nonambiguity set In each histogram, the bars represent disjunct stimulus subsets, together constituting the entire nonambiguity set For each subset, the histogram shows the size of the stimulus subset and the number of subjects for which the respective metric correctly predicted the responses to the stimuli in that subset In each histogram, the 11 leftmost horizontal positions show the subsets for which the respective metric prediction was significantly false, and the 11 rightmost horizontal positions show the subsets for which the respective metric prediction was significantly correct.

subset. For instance, the I_{new}-histogram applies to a nonambiguity set containing 186 of the 240 stimuli. From that histogram, one can read, for example, that, for one subset of 15 of the 186 stimuli, the I_{new}-load correctly predicted the responses of 20 of the 31 subjects and that, for another (disjunct) subset of 15 of the 186 stimuli, the I_{new}-load gave the correct predictions for 24 of the 31 subjects. So, from Figure 13, one readily sees that the I_A-load roughly performs better than the I_{old}-load since, in the I_A-histogram, larger subsets tend to be related to a larger number of subjects, i.e. more of the responses were predicted correctly. In the same way, one readily sees that the I_{new}-load roughly performs better than the I_A-load. So, at first glance, Figure 13 confirms the hypothesis. For a second glance, more detailed statistics are presented next.

First, for each metric, the predictions were compared to choice at chance level

($p=0.5$). The results of the t-test performed with the data (pooled across subjects) in Table 2, show that the I_{old}-load scores are highly significantly false(!) ($t_{30}=7.785$, $p<0.001$), that the I_A-load scores are just significantly correct ($t_{30}=2.088$, $p<0.05$), and that the I_{new}-load scores are highly significantly correct ($t_{30}=7.736$, $p<0.001$). Furthermore, within subjects, and again compared to choice at chance level, the I_{old}-load scored significantly ($p<0.05$) more correct predictions for only 1 subject. In contrast, the I_A-load scored significantly more correct predictions for 15 subjects, and the I_{new}-load scored significantly more for 24 subjects.

Metric	Size of set	Responses predicted correctly	
		mean +/- SD	%
I_{old}	150	56.0 +/- 13.6	37.3
I_A	136	74.6 +/- 17.6	54.9
I_{new}	186	124.4 +/- 22.7	66.9

Table 2. The means, standard deviations, and percentages of responses all predicted correctly by each metric for stimuli in the respective nonambiguity set.

Second, the metrics were compared by considering the respective proportions of significantly ($\alpha=0.05$) false and correct predictions (pooled across subjects); these results are presented in Figure 14. All differences between the proportions are highly significant, both for the significantly false predictions (I_A compared with I_{old}: $z=4.564$, $p<0.001$; I_{new} compared with I_A: $z=5.253$, $p<0.001$) as well as for the significantly correct predictions (I_A compared with I_{old}: $z=5.071$, $p<0.001$; I_{new} compared with I_A: $z=3.682$, $p<0.005$).

Third, in Figure 15, the proportions of significantly false predictions for stimuli in the respective nonambiguity sets are plotted again, but now together with the proportions of significantly false predictions for stimuli in the respective ambiguity sets. The differences between the latter proportions (i.e. for just the ambiguity sets) are not significant, but the differences between the summed proportions (ambiguity set plus nonambiguity set) are highly significant (I_A compared with I_{old}: $z=3.776$, $p<0.005$; I_{new} compared with I_A: $z=5.512$, $p<0.001$).

Fourth and finally, each metric was tested for a possible differentiation in response time between responses predicted correctly and responses predicted falsely (which can be done only for the nonambiguity sets). Figure 16 shows, for each metric, the average response times over all responses predicted correctly and over all responses predicted falsely; for the I_{old}-load, "false" response times tend to be shorter than "correct"

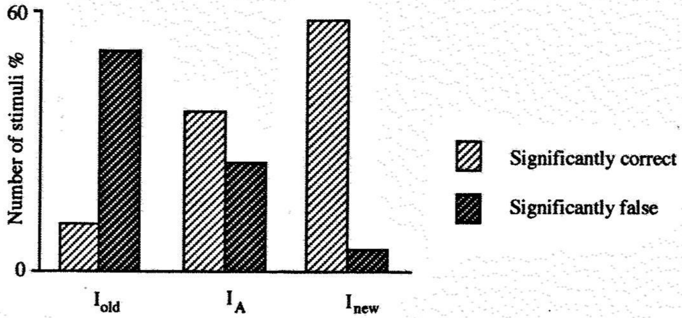


Figure 14. The proportions of significantly false and significantly correct predictions for the stimuli in the respective nonambiguity set for each metric. All differences between proportions are significant.

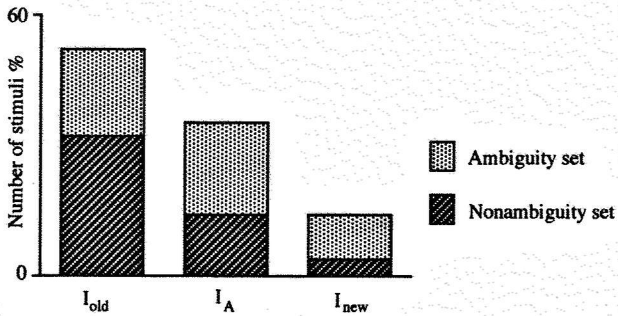


Figure 15. The proportions of significantly false predictions for the entire stimulus set, i.e. for both the ambiguity set and the nonambiguity set for each metric. For just the ambiguity sets, the differences between the proportions are not significant, but for the entire stimulus set the differences are significant.

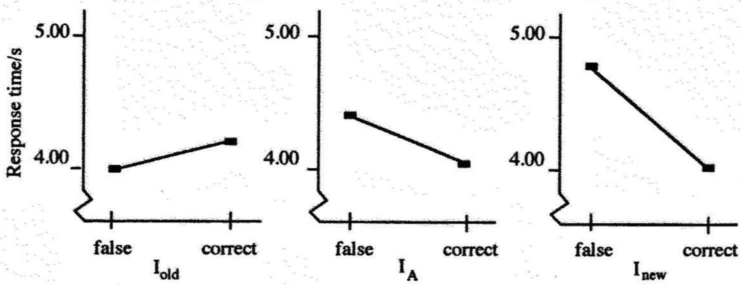


Figure 16. The average response times over all responses predicted falsely and over all responses predicted correctly (only for the respective nonambiguity sets) for each metric.

response times, whereas the other metrics yield an opposite tendency. An ANOVA was performed to check whether these tendencies might be influenced by the number of different elements in a target (two or three symbols) or by the total number of elements in a target (i.e. target "length" which varied from 5 to 18 symbols). The factor Length was set to four levels, and the factor Symbols was set to two levels. Then, for the I_{new}-load only, the factor Prediction (two levels: false or correct) yields a significant differentiation in response times (ANOVA over 4*2*2=16 cells; five subjects were rejected because of empty cells: $F(1,25)=5.88$, $p<0.05$). The factor Prediction does not interact with the factor Length nor with the interaction term Length x Symbols.

5.5 *Discussion*

The experimental results confirm the hypothesis. That is, the results not only confirm that the I_{new}-load is significantly better than both the I_A-load and the I_{old}-load, but also that the I_A-load is already significantly better than the I_{old}-load. The P-load scored 58.2% significantly false predictions for the stimuli in its ambiguity set which, as indicated before, almost equals the entire stimulus set. This implies that the P-load scored worst of all (see also Figure 15), and supports the earlier mentioned reasons for excluding the P-load from the analysis. For the three metrics considered in the analysis, the ordering in the goodness of the metrics is significant with respect to both the number of significantly correct predictions for the respectively nonambiguity sets, as well as the number of significantly false predictions for the entire stimulus set (see Figures 14 and 15).

The superiority of the I_{new}-load is supported further by its differentiation in response times between falsely and correctly predicted responses for stimuli in its nonambiguity set (see Figure 16). In general, we assume that such a differentiation takes place for a good predictor. That is, if subjects have more doubt about their preference, then an increase in response time results. So, inversely, if such an increase occurs consistently in case of false predictions, then the predictions may have been false but are apparently still good enough to "compete" with the actual responses. In the present experiment, the ANOVA on the response times showed a significant increase in response time on falsely predicted responses for the I_{new}-load only. So, adopting the assumption above, the response time results support the I_{new}-load only.

The goodness of the I_{new}-load may seem to be undermined somewhat by the fact that this metric scored "only" 57.5% significantly correct predictions for stimuli in its nonambiguity set (see Figure 14). However, as mentioned before, the selected stimuli had to be rather critical with respect to the metrics. For an arbitrary stimulus set, the predictions of the metrics are not very different, and the metrics score much better, as shown in earlier experimental work on the structural information model. Moreover, the main issue in this experiment was to compare the I_{new}-load with the I_{old}-load which scored the much smaller percentage of 11.3% significantly correct predictions (see

Figure 14).

One further remark in connection with the stimulus selection is that, as mentioned before, one of the criteria for selecting a target was that all ISA-rules should be used to generate the three possible response alternatives, so that the results indeed apply to the entire encoding model. Now, for all stimuli (target plus two response alternatives) in which one of the response alternatives is based mainly on the I-rule, the number of responses predicted correctly by the I_{new}-load is about two times as high as the number of responses predicted falsely. Exactly the same holds for the S-rule, and also for the A-rule. So, the I_{new}-load "treats" the ISA-rules in an equivalent way, which gives further confidence in the correctness of this metric.

Finally, the confirmation of the hypothesis implies strong support for the theoretical analysis of regularity and hierarchy, as elaborated in Van der Helm & Leeuwenberg (1991). As argued in the previous sections, that analysis leads directly to the ordering of the metrics according to goodness, that is now confirmed experimentally. So, the I_{new}-load is not only just a good metric, but it also has a firm theoretical basis which is supported by the experimental results.

6 Summary and conclusion

In this paper, we introduced a new metric to measure the complexity of serial patterns. Such a complexity metric is needed in pattern encoding models, like Leeuwenberg's (1969, 1971) structural information model. Such models employ several coding rules to describe possible structures of a pattern, and adopt the minimum principle by assuming that the simplest code of a pattern reflects the humanly preferred interpretation of that pattern. In brief, pattern interpretations are given in terms of pattern parts, i.e. a pattern segmentation (parts plus relation between parts) represents the pattern structure according to an interpretation, and the a simplest code of a pattern is a code that describes the largest amount of regularity in that pattern. In such encoding models, the employed complexity metrics are generally just "good guesses", formulated in terms of the encoding syntax and lacking an intrinsic psychological justification, whereas regularity is discussed merely in an intuitive sense.

The new complexity metric introduced in this paper, however, is based on a strictly formal analysis of regularity and hierarchy in patterns, as elaborated in Van der Helm & Leeuwenberg (1991). This formal analysis resulted in the notions of holographic regularity and of transparent hierarchy. The notion of transparent hierarchy applies to the conditions under which different but (partly) overlapping regularity structures can be combined hierarchically. The notion of holographic regularity represents a formalization of the intuitive notion of regularity, and results in a restricted number of basic kinds of regularity. Assuming that holographic regularity and transparent hierarchy are psychologically relevant notions, only three coding rules are needed to describe pattern structures, namely the Iteration rule, the Symmetry rule, and the Alternation rule, as used in Leeuwenberg's structural information model. The kinds of regularity described by these three coding rules were already widely accepted (intuitively) as being psychologically relevant, but now appear to have a unique formal status too. That is, in a strictly formal way, precisely these kinds of regularity result from the notions of holographic regularity and transparent hierarchy. This implies that these two notions can be seen as the underlying psychological basis of the description of pattern structures.

The plausibility of the formal analysis is supported further by two facts. First, it allows for a largely parallel encoding process. This supports the analysis since the fascinating speed with which the human perceptual system processes patterns is generally thought to result from parallel processing. Second, it allows for the elimination of combinatorial explosions. That is, it enables the selection of a simplest code out of the exponential number of possible codes, by taking into account all codes but without generating every code separately. This also implies support of the analyses since it shows that the minimum principle is realistic in the sense that it does not require an unrealistic search for simplest codes.

All in all, the formal analysis constitutes a firm basis for further research. In the present paper, we elaborated the fact that the formal analysis enables a detailed investigation into the way in which pattern complexity is quantified by means of complexity metrics used in earlier research. This investigation resulted in proposing a new complexity metric which, according to the formal analysis, should be superior to the metrics used before. That is, the new metric quantifies complexity by taking into account the irregularity in a code in the same way as in the other metrics, but it accounts for the hierarchy in a code in a better way. In particular, this improved account of hierarchy is relevant with respect to so-called local-effect cases, i.e. cases in which (with the old metrics) an a-priori pattern partitioning has to be assumed in order for the simplest code to reflect the preferred interpretation. This requirement contradicts the minimum principle. With the new metric, simplest codes tend to represent less hierarchically organized pattern structures and, therefore, tend to look like codes obtained by encoding pattern parts separately. This suggests that many local effects may "disappear" with the new metric, since it is not necessary to assume the proper pattern segmentation a priori because it follows directly from the simplest code.

The experiment discussed in this paper shows that the new complexity metric is indeed significantly better than the metrics used before. Moreover, and equally important, the experiment significantly supports the ordering of the metrics with respect to goodness, as was hypothesized on the basis of the formal analysis. This implies that we may conclude that the new metric is not merely a "better guess", but a plausible choice based on a formal analysis which is supported by the experimental results.

PART 2

SURFACES

"Unification by Simplicity"

Chapter 2

Integration of global and local aspects in visual occlusion

Abstract
The phenomenon of visual occlusion has frequently been studied by means of two-dimensional line drawings. These drawings may elicit various interpretations. Sometimes a mosaic of shapes is seen, sometimes a shape that partly occludes another shape. In the latter case, observers often have a clear idea about the form of the partly occluded shape. Local and global pattern aspects both seem to be decisive with respect to the preferred interpretation. An attempt is made to integrate these aspects by applying the global-minimum principle to the perceptual complexity of three distinct components of those pattern interpretations: i) The internal structure, dealing with each of the shapes separately, ii) the external structure, dealing with the positional relation between these shapes, and iii) the virtual structure, dealing with the occluded parts of the shapes. The perceptual complexity of each of these three components can be expressed in terms of structural information. The hypothesis that the perceptually preferred interpretation is the one for which the total information load is minimal is tested on many patterns stemming from different studies on pattern completion.

1 Introduction

Visual occlusion is a rule rather than an exception. In everyday life we mostly see parts of objects, yet experience them as being complete. The phenomenon of occlusion can be evoked by a two-dimensional line pattern, as in Figure 1. This pattern can be interpreted as a rectangle and an L-shaped form, but most observers have a strong preference for the interpretation in which a rectangle is positioned in front of a square.

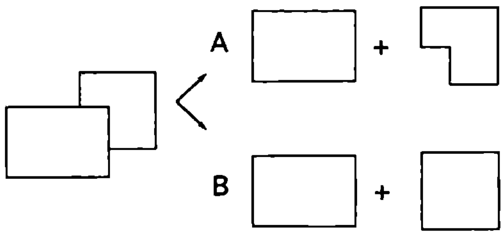


Figure 1. Two possible interpretations of one pattern. The occlusion interpretation (B) is preferred to the mosaic interpretation (A).

One might address two questions here. First, is completion of the background shape the result of a perceptual process or is it mainly based on cognitive processes? Second, what is the form of the background shape after completion? Gerbino and Salmaso (1987) and Sekuler and Palmer (1992) have made different attempts to answer the first question. Using a simultaneous-matching paradigm, Gerbino and Salmaso concluded that partly occluded shapes are functionally equivalent to complete shapes. In their simultaneous-matching task, the performance of subjects on partly occluded shapes did not differ from their performance on complete shapes. Sekuler and Palmer applied the so-called primed-matching paradigm to occlusion patterns. They concluded that completion of the background shape gradually develops over time and that within a small amount of time, as short as 200 ms, partly occluded shapes are represented perceptually as complete shapes.

Taking these experimental results as a strong indication of the perceptual relevance of occlusion phenomena, we will focus on the second question: the form of the completed background shape. Several studies on occlusion patterns have been done by various researchers (cf. Dinnerstein & Wertheimer, 1957; Michotte, Thinès, & Crabbé, 1964; Buffart, Leeuwenberg, & Restle, 1981; Rock, 1983; Boselie, 1988; Boselie & Wouterlood, 1989; Kellman & Shipley, 1991). A major distinction between the approaches of these authors is the distinction between so-called local and global theories. Stressing the influence of local cues, Kanizsa (1975, 1985, 1986) emphasized the role of good continuation in perceptual organization. Indeed, the preferred interpretation in Figure 1 (interpretation B) is predicted correctly on the basis of the good-continuation principle. This principle has been generalized and formalized by Kellman and Shipley (1991). They argued that completion will be such that the background shape is completed with the simplest continuous function between points of occlusion. Wouterlood and Boselie (1992) proposed a theory of visual completion that is completely based on local good continuation. However, their theory is designed to predict completions for a restricted set of shapes, i.e. shapes in which no regularities occur. Rock (1983) argued that the perceptual system avoids solutions with so-called unexplained regularities such as a coincidental meshing of borders. Despite the fact that Rock did not give a metric of coincidence, it is plausible that, according to Rock, the preferred completion in Figure 1 (interpretation B) is less coincidental than the alternative completion (interpretation A) in which a rectangle fits exactly in an L-shape.

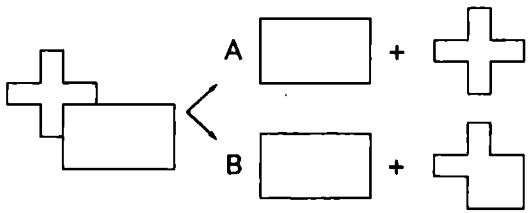


Figure 2. The mosaic interpretation (A) is preferred to the occlusion interpretation (B). The preference for interpretation (A) is predicted correctly by the global-minimum principle.

In contrast to local theories, global theories take into account regularities of the whole pattern. Early Gestalt psychologists (Wertheimer, 1923; Kohler, 1920) had indicated that perception tends to result in interpretations characterized by phenomenal simplicity and regularity. The Gestalt law of Prägnanz (Koffka, 1935) can be considered as the precursor of the global-minimum principle (Hochberg & McAlister, 1953), which states that the simplest interpretation of a pattern will be preferred. In the past, several descriptive models of visual patterns have been proposed (cf. Hochberg & McAlister, 1953; Leeuwenberg, 1969, 1971; Simon, 1972; Restle 1979). We will focus here on the Structural Information Theory (SIT) which combines the global-minimum principle with Leeuwenberg's coding model for visual patterns. Later on, we will give a brief account of the coding model as it has been elaborated by Van der Helm and Leeuwenberg (1991). This global approach also predicts that interpretation B of Figure 1 is preferred. The two shapes of this interpretation are more regular than are the shapes of interpretation A. However, there are patterns for which local and global theories predict different interpretations. A demonstration is given in Figure 2.

For Figure 2, the global-minimum principle correctly predicts that most subjects have a strong preference for interpretation A: a mosaic with a cross juxtaposed onto a rectangle. On the basis of the good-continuation principle, however, a preference for interpretation B would be predicted. Rock's coincidence-explanation principle does not lead unambiguously to one of the two solutions. On the one hand, interpretation B avoids a coincidental meshing of borders while, on the other hand, it leaves unexplained the coincidence of the symmetry of the visible cross.

In spite of an initial success of the global-minimum principle, patterns have been constructed (Kanizsa, 1985; Rock, 1983) that seem to contradict predictions made on the basis of this principle. Using the perceptual coding system within SIT, Boselie and Leeuwenberg (1986) were initially able to refute a number of counter examples that were brought in against the global-minimum principle. However, in two other studies, Boselie (1988) and Boselie and Wouterlood (1989) constructed and tested a great number of occlusion patterns, and found results in contradiction with predictions made by SIT. Figure 3 is taken from Boselie and Wouterlood (1989).

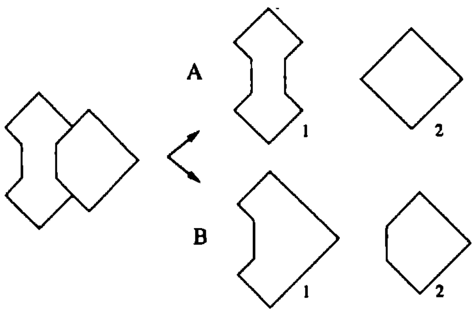


Figure 3. Interpretation B is preferred to interpretation A. This preference is not in line with the global-minimum principle as specified thus far.

In Figure 3, the two shapes in interpretation A clearly are more regular and therefore simpler than are the shapes in interpretation B. Yet, in a task in which subjects had to draw the contours of the perceived completion, none of the subjects showed a preference for interpretation A, whereas most of the subjects preferred interpretation B. Boselie and Wouterlood rightly remarked that the results do not necessarily imply a rejection of the global-minimum principle as such. This is in line with the work of Hatfield and Epstein (1985) who stated that a straightforward test of the global-minimum principle is not possible. The principle relies heavily on assumptions about what simplicity actually is. Yet, confronted with a large number of patterns that seemed to defy the global-minimum principle, Boselie (1988) suggested that locally simplest completions dominate in pattern completion. Furthermore, he stated that a globally simplest completion is made only in case of local ambiguity, i.e. when several locally simplest completions are possible. In any case, single factors such as familiarity, good continuation, local configurations, or coincidence appeared to be inadequate to explain the preferences of subjects.

What has to be done, in our view, is to examine both global and local aspects of occlusion patterns and determine their joint contribution to the complexity of pattern interpretations. With that basis, the global-minimum principle operates as a criterion to select the most preferred interpretation. First, however, we need to be clear about what the complexity of an interpretation actually refers to.

2 Perceptual complexity

We start with a distinction between two kinds of complexities. In order to illustrate this, we consider an analogy in the domain of problem solving. Problems may be difficult to solve. Yet it is common experience that a final solution may be astonishingly simple. Evidently, unravelling a problem is not the same thing as describing its solution. In our view, an analogous distinction is relevant for visual occlusion. That is, a distinction can be made between the acquisition of the preferred interpretation, and the interpretation itself as it might be stored in memory. Therefore, we make a distinction between the 'perceptual complexity' and the 'memory complexity' of an interpretation. The perceptual complexity refers to the complexity of an interpretation in relation to the pattern, whereas the memory complexity of an interpretation is determined by the memory space required to store that interpretation. To a certain extent, the posed distinction corresponds with the distinction between phenomenal simplicity and descriptive economy by Hatfield and Epstein (1985). However, the term phenomenal simplicity generally expresses a tendency to simplicity of shape. As we will see, in the case of occlusion patterns, simplicity of shape is just one aspect of the perceptual complexity of a certain interpretation. The notion of descriptive economy comes close to what we have called memory complexity. Nevertheless, we prefer the latter term because, as will be demonstrated, the determination of the perceptual complexity also proceeds in a descriptive way. We argue that, in order to predict preferred interpretations on the basis of complexity, the perceptual complexity has to be considered. In the remainder of this paper, the perceptual complexity of an interpretation will be discussed in more detail.

We will consider three components in visual occlusion that determine the perceptual complexity of an interpretation: *shape*, *position* and *occlusion*. These components are embedded in three different types of structure, termed the 'internal structure', the 'external structure', and the 'virtual structure', respectively (see Figure 4). We will clarify these three concepts and show that each of them independently affects the preference for perceptual interpretations of occlusion patterns. Furthermore, it will be argued that the sum of the perceptual complexities of the three structures determines the perceptual complexity of an interpretation. Finally, applying the global-minimum principle, we hypothesize that the total perceptual complexity of the most preferred

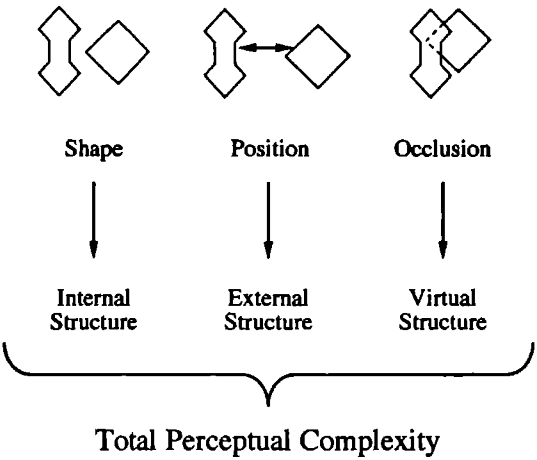


Figure 4. Three components, shape, position, and occlusion, are reflected by three types of structure. The total perceptual complexity of a pattern interpretation is constituted by the sum of the perceptual complexities of the three structures.

interpretation is lower than that of any other interpretation. As the quantification of the perceptual complexities of the three structures proceeds in terms of structural information, we first introduce the concept of structural information.

3 Structural information

We explicate the notion of structural information by considering symbol series. By means of a set of coding rules (Van der Helm & Leeuwenberg, 1991) regularity is extracted from such a series. In the structural information model only three classes of regularity play a role, namely iterations, symmetries and alternations. Each of these three classes can be described by a corresponding coding rule. In Table 1, an example is given for each of the three coding rules: The symbol series 'aaa' is encoded by means of the Iteration rule and results in the code '3*(a)', 'abcba' is encoded by the Symmetry rule, resulting in the code 'S[(a)(b),(c)]', and 'abac' is encoded by the Alternation rule, resulting in the code '<a>/<(b)(c)>'.

Each code comprises a certain amount of structural information. Now, given a specific symbol series, the aim is to find a minimum code, i.e. a code with a minimal amount of information. We will briefly sketch the way in which the amount of structural information is determined. Detailed discussion on this topic can be found elsewhere (Van der Helm & Leeuwenberg, 1991; Van der Helm, Van Lier, & Leeuwenberg, 1992). In Van der Helm et al. (1992) a new metric of structural

Regularity	Symbol series	Code	I
Iteration	aaa	3x(a)	1
Symmetry	abcba	S[(a)(b),(c)]	3
Alternation	abac	<(a)>/<(b)(c)>	3

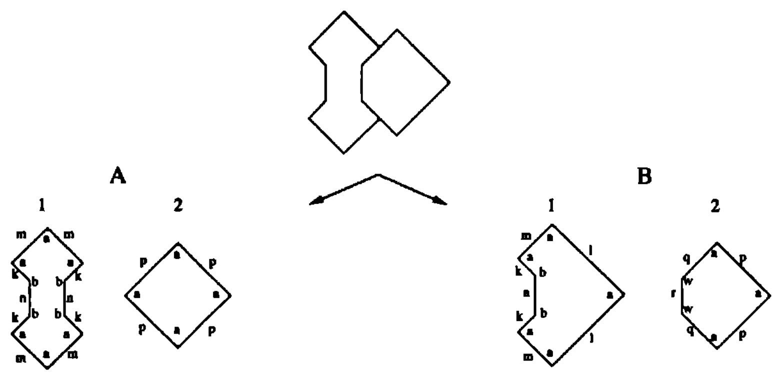
Table 1. The three types of regularity employed in the Structural Information Theory. Encoding of a symbol series proceeds by extracting these regularities from the series. The information load, I, of the code reflects the amount of irregularity.

information was proposed and tested on symbol series. This information metric takes into account all parameters at all hierarchical levels in the code. The number of parameters in a code of a symbol series determines the amount of irregularity in the series according to that code. The amount of structural information therefore reflects this amount of irregularity. Applying this notion to the codes in Table 1, the information loads are 1 (because of parameter ’a’), 3 (parameters ’a’, ’b’, and ’c’), and 3 (parameters ’a’, ’b’, and ’c’), respectively. Note that coding operations, reflected by for instance the ’S’-symbol in a code, are not considered as an information load. Note further that each code in Table 1 contains only one hierarchical level. In order to provide some examples of a hierarchical code consider the minimum codes of the symbol series ’ababab’ and ’abcab’. The minimum code of the series ’ababab’ is given by ’3*(ab)’. The information load of this code equals 3, constituted by the parameters ’a’ and ’b’, and the group ’ab’, which is treated as one entity as it is in fact a parameter at a higher level in the code. The encoding of ’abcab’ into ’S[(ab),(c)]’ yields an information load of 4, constituted by the parameters ’a’, ’b’, ’c’, and the group ’ab’. In contrast to this code, one may consider the encoding of ’abcba’ into ’S[(a)(b),(c)]’, which has only one hierarchical level and an information load of 3.

The encoding, from the initial symbol series to the selection of the code with the lowest information load, is completely processed by the computer program PISA (Van der Helm, 1988). There is an essential conceptual difference between metrics of information that were applied in the past and the new information metric mentioned above. In early versions of SIT (Leeuwenberg, 1969, 1971; Buffart, Leeuwenberg, & Restle, 1981) the required memory space to store a code was considered as the basis for their information metric. This old information metric, therefore, conceptually fits in with the notion of memory complexity. In the concept of the new information metric, however, this memory argument has been rejected and replaced by the irregularity argument described above. This irregularity argument emphasizes the relationship between code and symbol series. Therefore, the new information fits in with the notion of perceptual complexity. The quantification of the perceptual complexity of the interpretations of occlusion patterns by means of structural information is possible after operationalizing the perceptual complexities of the three structures that are involved. We start with the internal structure.

4 The internal structure

The internal structure of an interpretation involves the shapes within that interpretation. Accordingly, its perceptual complexity is constituted by the complexities of these shapes. To determine the complexity of a shape, the shape is represented by a symbol series. Every contour element, line or angle, is represented by a symbol such that equal elements are represented by equal symbols. The order of appearance of sequential elements on the contour is preserved in the order of the respective symbols in the series that represents the shape. This series is called the primitive code of the pattern. The encoding of the symbol series proceeds cyclically, i.e. irrespective of the element on the contour that is represented by the first symbol. The information load of the minimum code determines the complexity of the shape. Thus, the total complexity of the internal structure of an interpretation is made up of the sum of the complexities of all shapes within that interpretation. In the following, the information load of the internal structure will be referred to as '$I_{internal}$'.



1: aS[S[((m))((a))((k))((b)),((n))],(a)] Information load= 7
2: 4*(pa) Information load= 3
$I_{internal}$ =10

1: S[S[((a)),((m))]((k)(b)),(n)]S[(l),(a)] Information load= 7
2: S[(a)(q)(w),(r)]S[(p),(a)] Information load= 6
$I_{internal}$ =13

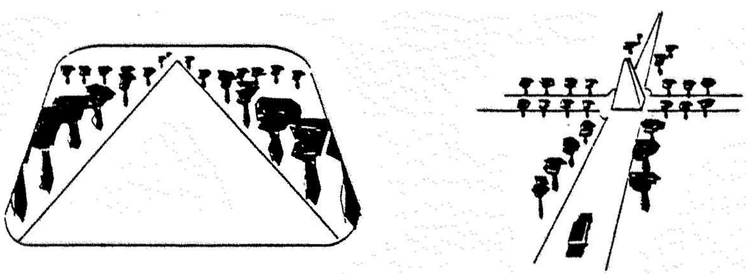
Figure 5. The calculation of $I_{internal}$ performed for two different interpretations of a pattern. First, each shape within an interpretation is represented by a symbol series such that all lines and angles are represented each by one symbol, and such that their order and identity are preserved. Second, each symbol series is encoded, resulting in a minimum code. The information load for each code equals the number of descriptive parameters in the code (indicated by a dot). Third, $I_{internal}$ of the interpretation is calculated by summing the information loads of the minimal codes.

In Figure 5, the minimum codes and their information loads are presented for the shapes within both interpretations of the pattern in Figure 3. For example, within interpretation A, the second shape is a square represented by symbol series 'papapapa'. The minimal code of this series is obtained by applying the Iteration rule, resulting in '4*(pa)'. The amount of information is calculated by counting the total number of parameters, i.e. 'p', 'a', and 'pa': thus I=3. The determination of the complexities of the other shapes proceeds in a similar way. Next, the total complexity of the internal structure for a specific interpretation is calculated by summing the complexities of the internal structure of both shapes within that interpretation. It appears that interpretation A has a lower $I_{internal}$ than does interpretation B (the values being 10 and 13, respectively). As interpretation B is preferred to interpretation A, it is clear that a 'simplest-shape' operationalization of the minimum principle, based solely on the internal structure, leads to a wrong prediction.

Once an occlusion pattern has been interpreted, and the perceived shapes have to be memorized, the internal structure suffices. However, in interpreting the pattern, the perceptual complexities both of the external and of the virtual structure also play a role. We first take a closer look at the external structure. The section on the external structure is rather extensive, as it introduces some new concepts which require a more detailed discussion.

5 The external structure

The external structure of an interpretation applies to the positional relation between the shapes within that interpretation. It is well known that the relative position of objects affects perception. Let us consider an extraordinary case. Imagine a somewhat misty road. In Figure 6A a view of the road, as momentarily seen through the windscreen of a car, is depicted: the road seems to be straight ahead to the horizon. The real situation may be quite different, for instance including an obelisk, as depicted in Figure 6B.



A B

Figure 6. Two possible views of the same situation. In A, a view through the windscreen of a car is depicted, whereas B may be a bird's eye view. Obviously, the point of view of the car driver induces a coincidental alignment of borders. Due to this alignment, the car driver's interpretation of the scene does not involve an obelisk.

Nevertheless, Figure 6A will be interpreted as 'only a road' and not as 'road plus obelisk'. The reason for this interpretation clearly lies in the fact that, in Figure 6A, the 'road plus obelisk' interpretation implies coinciding contours of the road and the obelisk, whereas the 'only a road' interpretation does not imply such coincidences. How should one understand the role of such coincidences, and how can their effect be quantified? We will discuss both issues successively.

According to the general-viewpoint principle (cf. Huffman, 1971), the positions of the perceiver and the objects in the scene are assumed to be general, i.e. coincidences are assumed not to be present in the momentary percept. In this way, the 'road plus obelisk' interpretation is not even considered as one of the possible interpretations. Similarly, but less rigorously, Rock (1983) argues that the perceptual system avoids interpretations which imply coincidences that are caused by unexplained regularities or co-occurrences. In this way, the 'road plus obelisk' interpretation may be considered as one of the possible interpretations, but is rejected in favour of the 'only a road' interpretation since the former interpretation implies unexplained regularities (i.e. the coinciding contours of road and obelisk), whereas the latter interpretation does not. Note that Rock does not use the term 'probability' as such in order to explain these preferences, as probability also may include the influence of past experience. Nevertheless, in the following we will use the term probability, but solely in the context of regularity, thereby excluding past experience. Now, let us take a closer look at the role of coincidences by means of Figure 7.

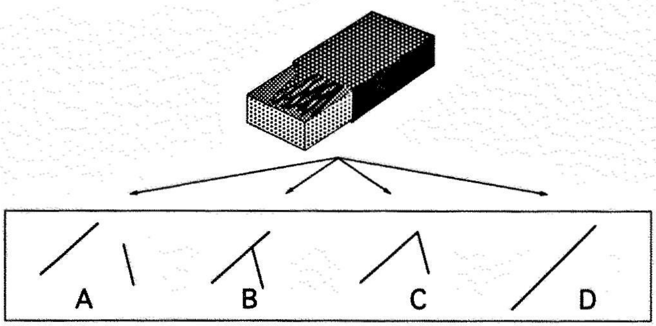


Figure 7. Four random throws of two matches are represented (A-D). Most observers do not regard each of these configurations as equally probable. The configurations on the left look more probable than do the configurations on the right. The solution to this incongruity is that, as a result of a random throw, there are more configurations like those on the left than there are like those on the right.

In Figure 7, four random throws of two matches are depicted. Somehow, the configurations on the left look more probable than the configurations on the right. It is obvious, however, that each specific configuration has an equal probability of being the result of a random throw. The solution to this incongruity is that the kinds of configurations in Figure 7 are not equally probable: among all possible configurations, there are more configurations like that in Figure 7A than there are like that in Figure 7D. For this reason supporters of the coincidence-explanation principle do not consider the probability of a specific configuration, but the probability of occurrence of a perceptually salient feature, such as the T-junction in Figure 7B. This means that the probability of a specific configuration is based on the perceptual classification of that configuration. In this way, it can indeed be argued that different interpretations, like those mentioned above for the momentary percept in Figure 6A, differ in probability and that the most probable one is selected. But then, two questions arise. First, how is it established to which class an interpretation belongs? Second, how is the probability for that class determined? Only if these two questions are answered might probability be acceptable as a basic explanatory principle.

In our view probability merely functions as a secondary concept. Our arguments are as follows. Given an interpretation of a momentary percept, coinciding positions are just regularities caused by the positional relation between the objects in the interpretation. So, just like the internal structure of an interpretation, the positional relation too is a source of regularities. Now in our approach, an interpretation is represented by a description and a quantification of the regularity in that interpretation, which implies classification. That is, the interpretation belongs to the class of all interpretations that contain precisely the same kinds of regularity and the same degree of regularity (Collard & Buffart, 1983). Collard and Buffart also demonstrated that the greater the degree of regularity in an interpretation, the smaller the class to which that interpretation belongs. So, in fact, the probability of a specific interpretation could be related directly to the degree of regularity already quantified (i.e. the number of descriptive parameters) in that interpretation.

Note that our line of reasoning provides answers to the two questions raised above. Also note that it implies that any probability calculus based on the number of descriptive parameters reduces itself to a secondary concept (see also Leeuwenberg & Boselie, 1988). That is, in our view, probability is not the basis for the perceptual role of coincidences, but merely a postperceptual side effect based on the perceptual role of regularities.

Now that we have explained our views of the role of coincidences or regularities in the positional relation between objects, we can turn to the quantification of their effects. In the following we will refer to this positional relation as the 'external structure' of an interpretation. On the one hand, regularities in the external structure of an interpretation would reduce the memory complexity of an interpretation, as they enable a simpler description of an already available interpretation. On the other hand, however, in interpreting a pattern, regularities in the external structure of an interpretation form a perceptual obstacle with respect to that interpretation. Perceptually, these regularities have a binding effect on the pattern parts that, within the interpretation, are considered to be independent objects. For instance, the pattern in Figure 7D on its own is hardly interpreted as a concatenation of two independent objects (represented by line elements). Thus, coincidences enlarge the perceptual complexity of an interpretation, because the coinciding object parts have to be "dissociated" perceptually. This dissociation eliminates the regularities in the external structure by adding the same amount of irregularities. The quantification of the perceptual complexity of the external structure of an interpretation is shown in Figure 8.

Considering the hook-like pattern of Figure 8A as one object, it can be described by three parameters 'l', 'a' and 'm' representing a line, an angle, and a line, respectively. Another interpretation may be two separate line elements, representing for instance two sticks. In order to determine the perceptual complexity of the external structure of the latter interpretation, a dissociation of the sticks has to be established, such that there are no regularities left between them (see Figure 8B). The pattern in Figure 8B can be described by 5 parameters 'l','p','q','r', and 'm' representing a line, an angle, a distance between the lines (indicated by the dashed line), an angle, and a line, respectively. The difference in the number of descriptive parameters for the actual pattern (Figure 8A) and the dissociated pattern (Figure 8B) is entirely due to the variation in the relative position of the sticks in the two patterns. This difference (5-3=2) therefore reflects the degree of irregularity, in terms of structural information, that has to be added to the actual pattern in order to establish the dissociation. Therefore, this amount of structural information is taken to be the perceptual complexity of the external structure of the 'two-sticks' interpretation. The complexity of the external structure will be referred to as $I_{external}$.

In the following we will apply this calculation strictly locally at each junction within a pattern. Consider for example the pattern in Figure 9A. This pattern can easily

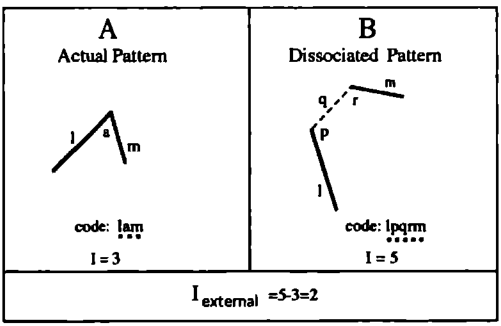


Figure 8. The hook pattern (A) may be interpreted as two independent sticks. The perceptual complexity of the external structure of this interpretation is quantified by subtracting the number of descriptive parameters needed to describe the actual pattern (A) from the number of descriptive parameters needed to describe the dissociated pattern (B). All descriptive elements are indicated with a dot.

be conceived as a juxtaposition of two triangles. In Figure 9B a dissociation of these two triangles is depicted. The junction that constitutes the connection between the triangles in the actual pattern is shown in Figure 9A'. Note that, as the determination of $I_{external}$ proceeds locally at each junction, all lines at the junction have been drawn with an arbitrary length. Accordingly, all line elements have been labelled with different symbols. So, only the specific way in which they are connected is decisive with respect to $I_{external}$. In Figure 9B' the junction has been dissociated, according to the dissociation of the two triangles. In order to calculate the complexity of the external structure, we will first determine the minimal number of descriptive parameters for the junction in Figure 9A'. The description proceeds by tracing the line elements of the junction, thereby fixating their relative position. For example, the junction of Figure 9A' may be described as follows. Starting with line 'l' (see arrow in Figure 9A'), there is a bifurcation such that lines 'l' and 'p' include an angle 'a'; there is a second bifurcation where lines 'l' and 'q' include an angle 'b', and finally, line 'l' continues - without changing direction - into line 'm'. This description enables one to reconstruct this particular junction. Note that all other angles in the junction are implicitly given in the posed description. So, a primitive code for that junction is 'l{ap}{bq}m' (the brackets within the code express a bifurcation, cf. Leeuwenberg, 1971). This code, which cannot be reduced by coding rules, contains 6 parameters and therefore has an information load of 6. Other codes are possible, but would not result in a lower information load. We

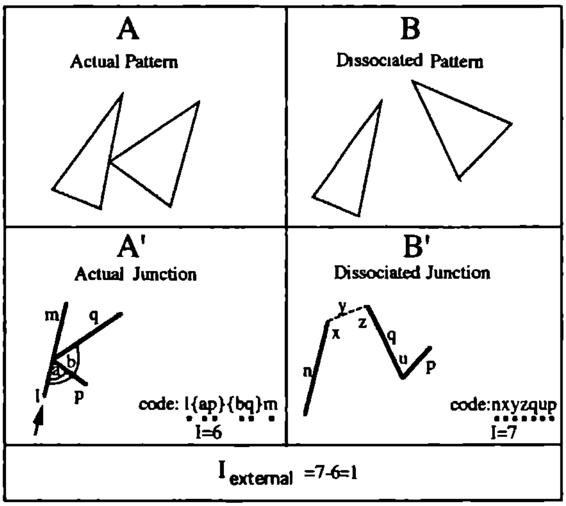


Figure 9. The calculation of $I_{external}$ for the junction between two triangles. The two triangles are shown joined (A) and dissociated (B). The junction that constitutes the connection between the two triangles in the actual pattern is also shown joined (A') and dissociated (B'). The codes for the two junctions are shown as well; the descriptive parameters are indicated by dots. See text for details of calculation.

now turn to the dissociated junction (Figure 9B'). All lines and angles are labelled again, including the distance and angles between the contours. One parameter 'n' is required for the description of the junction part that stems from the edge of the left triangle, three parameters ('q', 'u', and 'p') are required for the junction part that stems from the corner of the right triangle and three parameters ('x', 'y', and 'z') specify the relative position of the two dissociated junction parts. The corresponding code ('nxyzqup') therefore contains 7 parameters. As in the example in Figure 8, the

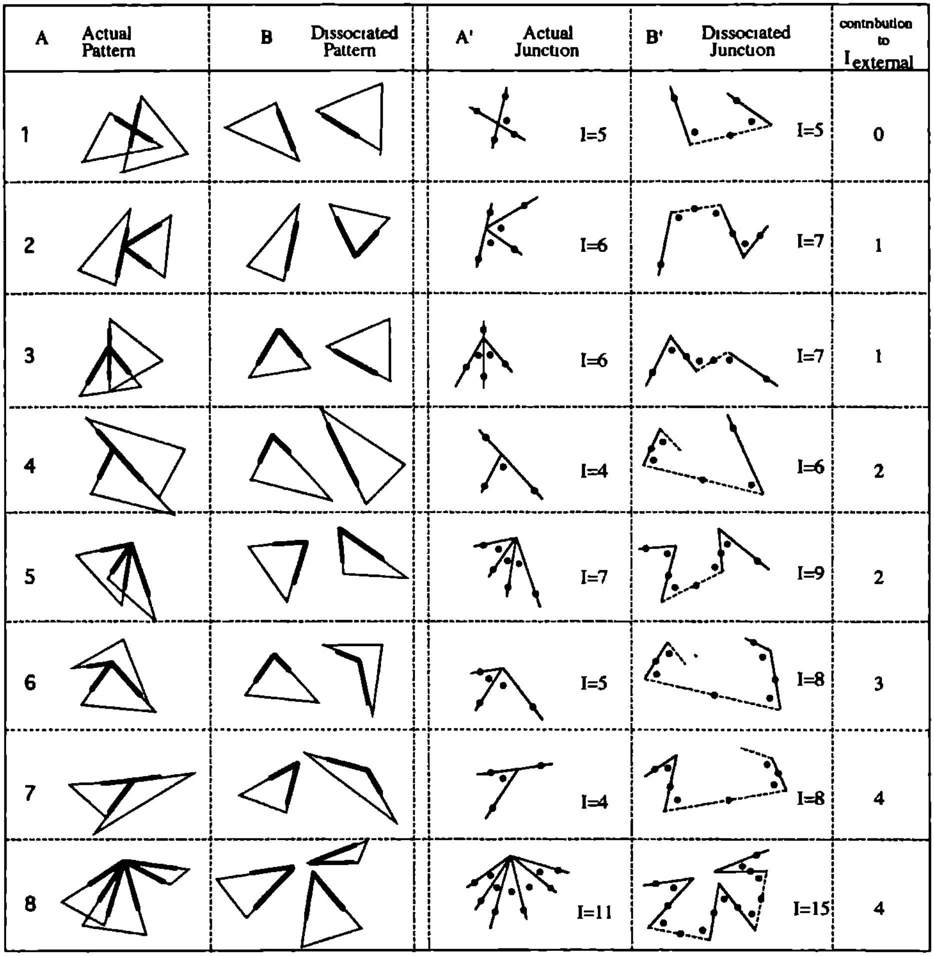


Figure 10. The calculation of the contribution to the complexity of the external structure of a pattern for various junctions that may arise between contours of shapes. The bold lines indicate the junction to be considered. In the two columns showing the actual and dissociated junctions the black dots indicate the minimal number of descriptive parameters needed to describe the junction.

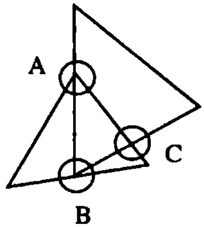
Pattern	Contribution to $I_{external}$
	Junction A: 1 Junction B: 1 Junction C: 0
$I_{external} = 2$	

Figure 11. Pattern 3 of Figure 10, enlarged. Three junctions appear, labelled A, B, and C. The assessment of the complexity of the external structure of this pattern proceeds by summing the separate contributions to the external structure for all junctions in the pattern.

complexity of the external structure is given by the difference between the complexity of the dissociated junction and the complexity of the actual junction. Therefore $I_{external}=7-6=1$.

In the following we will, for reasons of simplicity, just indicate the minimal number of parameters that is required to describe the junction and its dissociation. In the drawings, these parameters will be indicated by dots. In Figure 10 the contribution to $I_{external}$ is determined for junctions of various patterns. For each pattern in the first column in Figure 10, only one specific junction is considered. That junction is indicated with bold lines. The calculation of $I_{external}$ proceeds analogously with that in the previous examples.

So far, the contribution to the complexity of the external structure has been calculated for just one junction within a pattern. However, other junctions in a pattern might also increase $I_{external}$. Let us consider Figure 11, in which pattern 3 of Figure 10 has been drawn once more. In this pattern three junctions appear, labelled A, B, and C. Junction A is the same as the one considered for pattern 3 in Figure 10. So, junction A yields a contribution of 1 to $I_{external}$. Junction B, in which a corner of a triangle adjoins an edge of another triangle, reveals the same situation as in Figure 9, or as in pattern 2 of Figure 10. Hence, junction B also yields a contribution of 1 to $I_{external}$. Finally, the contribution of the crossing lines of junction C to $I_{external}$ is the same as for the junction considered for pattern 1 in Figure 10. In that case the actual junction and the dissociated junction have the same information loads. Therefore, junction C yields a contribution of 0 to $I_{external}$. Now, the complexity of the external structure for the complete pattern interpretation (i.e. two triangles) is calculated by taking the sum of these three contributions. So, $I_{external}=2$.

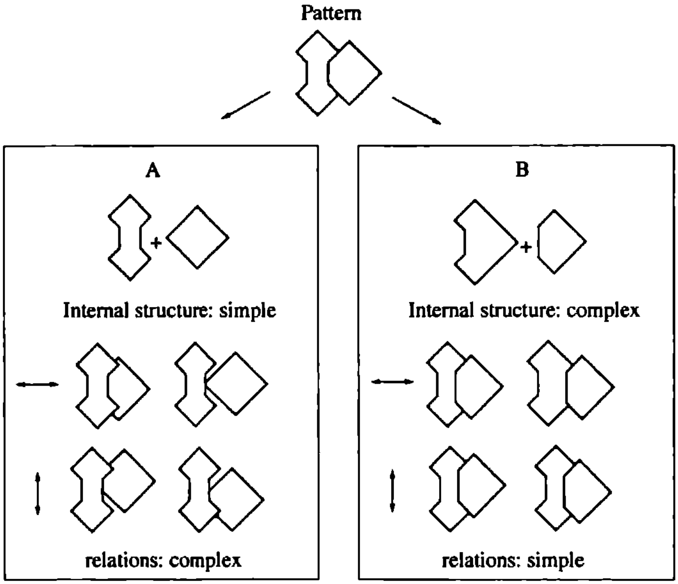


Figure 12. Dissociations of shapes for two different interpretations of one pattern. In interpretation A, the internal structure of the interpretation is simpler than in interpretation B, yet the dissociations for A causes a larger change in the positional relation of the shapes than do the dissociations for B.

As the calculation of $I_{external}$ has now been set, we turn to occlusion patterns. Consider again the pattern in Figure 3. This pattern and its interpretations, A and B, are depicted once more in Figure 12. In order to visualize some dissociations of the shapes within each interpretation, small translations are applied in different directions. As a result of these small translations associated contour elements, that belong to different shapes, become dissociated in the generalized positions. Apparently the translations cause more drastic changes for interpretation A than for interpretation B. Therefore it can be expected that $I_{external}$ of interpretation A will be higher than $I_{external}$ of interpretation B. In Figure 13, $I_{external}$ is determined for both interpretations of the pattern. We start with interpretation A. The junctions are labelled a1 to a4. Note that junctions a1 and a4 are exactly the same. This also holds for junctions a2 and a3. The calculation of the contribution to $I_{external}$ for these junctions is shown in Figure 13A'. Actually, the calculation is the same as performed for the junction of pattern 4 in

Figure 10, which yielded a contribution of 2 to $I_{external}$. Hence, $I_{external}$(interpretation A)=4*2=8. Within interpretation B there are two identical junctions (labelled b1 and b2). The calculation for these junctions, shown in Figure 13B', is the same as that performed for the junction of pattern 1 in Figure 10, which yielded a contribution 0 to $I_{external}$. Hence, $I_{external}$(interpretation B)=0.

The determination of the perceptual complexity of the external structure by taking the sum of the contributions to $I_{external}$ over all junctions in a pattern enables an unambiguous calculation of $I_{external}$. One may argue that other relational properties between pattern and interpretation codetermine the complexity of the external structure. For instance, interpretation B in Figure 3 induces a special position of shapes, as this position is such that the visible part of shape B1 is a nice regular shape, equivalent to shape A1. Now, should the regularity of the visible part of an occluded shape therefore increase $I_{external}$? Our answer is no. The regularity of shape A1 is already captured in the internal structure of interpretation A. Therefore, this regularity as such supports interpretation A, instead of suppressing interpretation B, so it does not have to be accounted for when considering interpretation B.

Summarizing, the external structure deals with regularities between the objects, whereas the internal structure concerns regularities within the objects. In both cases,

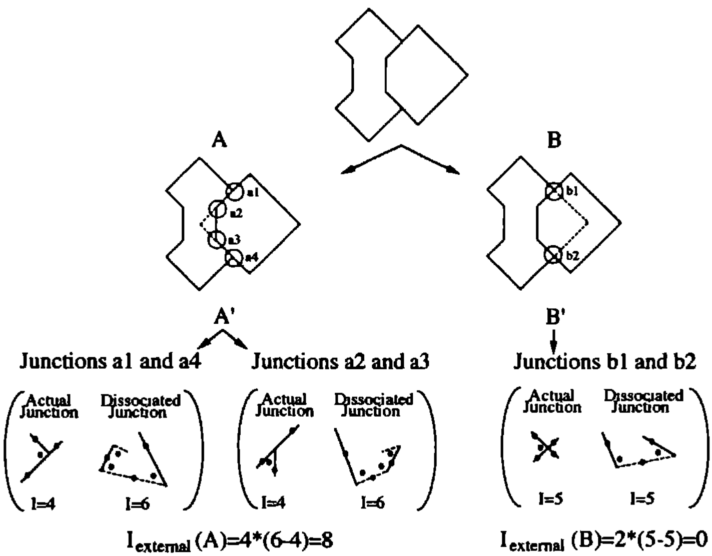


Figure 13. The calculation of the perceptual complexity of the external structure of two possible interpretations of one pattern. For each junction, the number of descriptive parameters for the actual position is subtracted from the number of descriptive parameters for the dissociated position. The perceptual complexity of the external structure for each interpretation is determined by the sum of these differences over all junctions.

these regularities will bind pattern elements. The binding in the internal structure strengthens an interpretation, whereas the binding in the external structure weakens an interpretation. In addition to these two structures there is a third structure that plays a role, namely the virtual structure.

6 The virtual structure

Whenever completions occur, there is a discrepancy between the number of pattern elements in the proximal stimulus and the number of elements within an interpretation. Virtual elements are added to complete the occluded shape. These virtual elements constitute the virtual structure of the interpretation. Note that for an already-available interpretation, the virtual elements are part of the shapes and therefore do not contribute to the memory complexity of that interpretation. Patterns can be made, however, in which several alternative interpretations have the same perceptual complexity both for the internal structure and for the external structure, but which evoke a clear preference for only one specific interpretation. Such a case is shown in Figure 14. Interpretation A is preferred to interpretation B, presumably because of its relatively simple virtual structure. Therefore, the contribution of the virtual structure to the perceptual complexity of a pattern interpretation is considered to be independent of the contributions of the other structures.

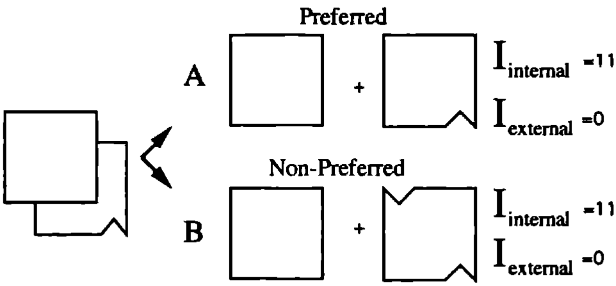


Figure 14. For the interpretations of the pattern on the left, both $I_{internal}$ and $I_{external}$ are equal. Yet, interpretation A is preferred to interpretation B, presumably due to the fact that the occluded part in A is relatively simple.

To quantify the perceptual complexity of the virtual structure, we will make an intuitively appealing assumption: The perceptual complexity of an interpretation increases with the number of virtual elements, i.e. additional lines and angles. Our argument is that, before primitive codes of the internal structure can be reduced by means of encoding, the primitive virtual elements have to be available. Insofar as completion does not unify different visible line elements into a single element (by means of continuation), the number of virtual elements is specified by the difference between the number of visible elements of the partly occluded shape and its total number of elements. In the following, the quantification of the perceptual complexity of the virtual structure will be referred to as $I_{virtual}$. With respect to the pattern in Figure 3, the complexity of the virtual structure is the same for both interpretations (see Figure 15). In both interpretations, $I_{virtual}$ equals 1. Notice that this number is not necessarily equal to the number of elements of the occluded part. In Figure 15, this part in both cases is a hook pattern containing 3 elements, but $I_{virtual}$=1. In fact, the definition of $I_{virtual}$ implies that continuation of a visible line behind an occluding shape does not introduce a new virtual element and therefore does not increase $I_{virtual}$.

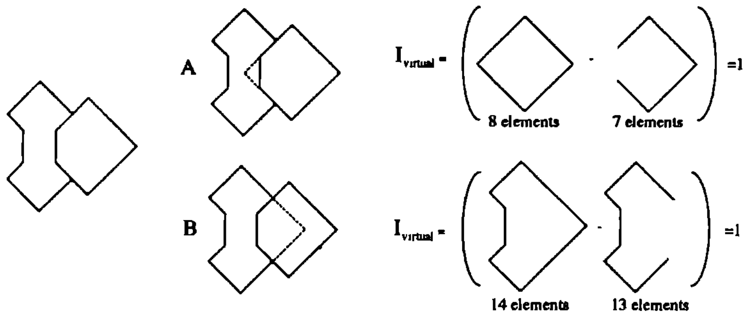


Figure 15. The perceptual complexity of the virtual structure of interpretations A and B is calculated by subtracting the number of visible elements of the partly occluded shape from its total number of elements.

7 Testing the theory

We define the total perceptual complexity of an occlusion interpretation as the sum of the perceptual complexities of the three types of structure:

$$I_{total} = I_{internal} + I_{external} + I_{virtual} \ .$$

In Figure 16, this summation has been performed for the interpretations of the pattern in Figure 3 (the complexities for both interpretations have already been calculated in sections 4, 5, and 6). I_{total} appears to be lower for interpretation B, which was indeed the most preferred interpretation. In order to test I_{total} on a broad range of critical patterns we have made use of published patterns and data stemming from three different papers: Buffart, Leeuwenberg, and Restle (1981) (25 patterns), Boselie (1988) (27 patterns) and Boselie and Wouterlood (1989) (92 patterns). Thus, in total 144 patterns have been considered. The first paper was selected because in it the applicability of SIT to completion patterns was claimed. The latter two papers were chosen because they contain a great number of patterns that appeared to be in contradiction with predictions made by SIT. In contrast to the present study, in the previous studies predictions were made solely on the basis of the internal structure of interpretations, and an old metric of information, based on memory capacity, was used. The experimental procedure in each of those studies was the same: given a pattern, subjects were asked to draw the contours of their spontaneous pattern interpretation on a piece of paper.

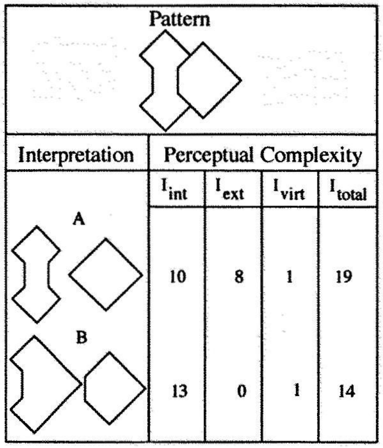


Figure 16. The total perceptual complexity of a pattern interpretation is calculated according to the expression: $I_{total} = I_{internal} + I_{external} + I_{virtual}$. In this case, it appears that the interpretation with the simplest shapes (A) results in a higher perceptual complexity than does interpretation B, which was the most preferred interpretation.

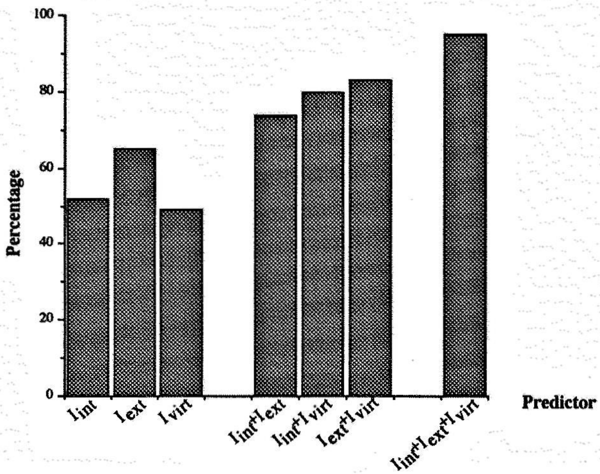


Figure 17. The percentage of patterns for which the most preferred interpretation is predicted correctly according to the three structure complexities and their combinations.

In 52% of all patterns, $I_{internal}$ is the lowest for the most preferred interpretation, and therefore correctly predicts that interpretation. In 65% of all patterns, $I_{external}$ correctly predicts the most preferred interpretation, and in 49% of all patterns this is the case for $I_{virtual}$. However, when taking the sum of these three complexities, it appears that in 95% of all 144 patterns I_{total} correctly predicts the most preferred interpretation. In Figure 17 these percentages are depicted. The percentage of correct predictions as a function of the pairwise combinations of the three structure complexities are also depicted (74% for $I_{internal}$+$I_{external}$, 80% for $I_{internal}$+$I_{virtual}$, and 83% for $I_{external}$+$I_{virtual}$).

As can be verified in the histogram in Figure 17, there is an overlap in the correct predictions made by the separate structure complexities. The exact overlap is made visible in the Venn diagram shown in Figure 18. It can be seen that in 15% of all cases only $I_{internal}$ is the lowest for the most preferred interpretation. In 10% of all cases this holds for $I_{external}$ and in 14% of all cases for $I_{virtual}$. In 27% of all cases, both $I_{internal}$ and $I_{external}$ correctly predict the most preferred interpretation. In 25% of all cases, this holds for $I_{external}$ and $I_{virtual}$, and in 7% of all cases for $I_{internal}$ and $I_{virtual}$. In only 3% of all patterns are all three complexities the lowest for the most preferred interpretation. Notice that for all examined patterns at least one of the three complexities is the lowest for the most preferred interpretation. Finally, we examined whether the difference in I_{total} between alternative interpretations for a given pattern is related to the degree of preference for a specific interpretation. This is done by correlating the preference for the simplest-shape interpretation with the proportion I_{total}(simplest-shape interpretation)/I_{total} (second-best interpretation): $r=0.76$, $p<0.001$.

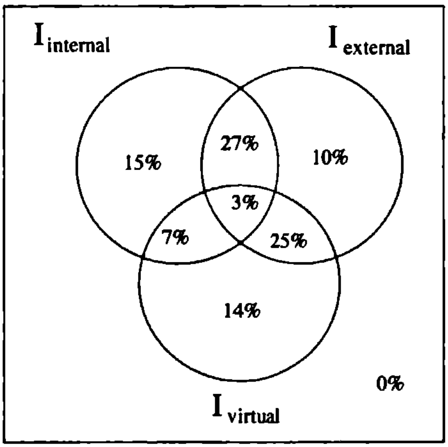


Figure 18. Venn diagram showing the amount of overlap in correct predictions according to the separate structure complexities. Note that for all examined patterns at least one of these complexities is the lowest for the most preferred interpretation.

8 Discussion

For the greater part (95%) of the 144 patterns considered, the most preferred interpretation is predicted correctly by the global-minimum principle, by the use of the proposed quantification of the total perceptual complexity (I_{total}) of interpretations. I_{total} was defined as the sum of the perceptual complexities of the internal structure, the external structure, and the virtual structure of an interpretation. Considering the proportion of correct predictions based on the complexity of each of the three structures

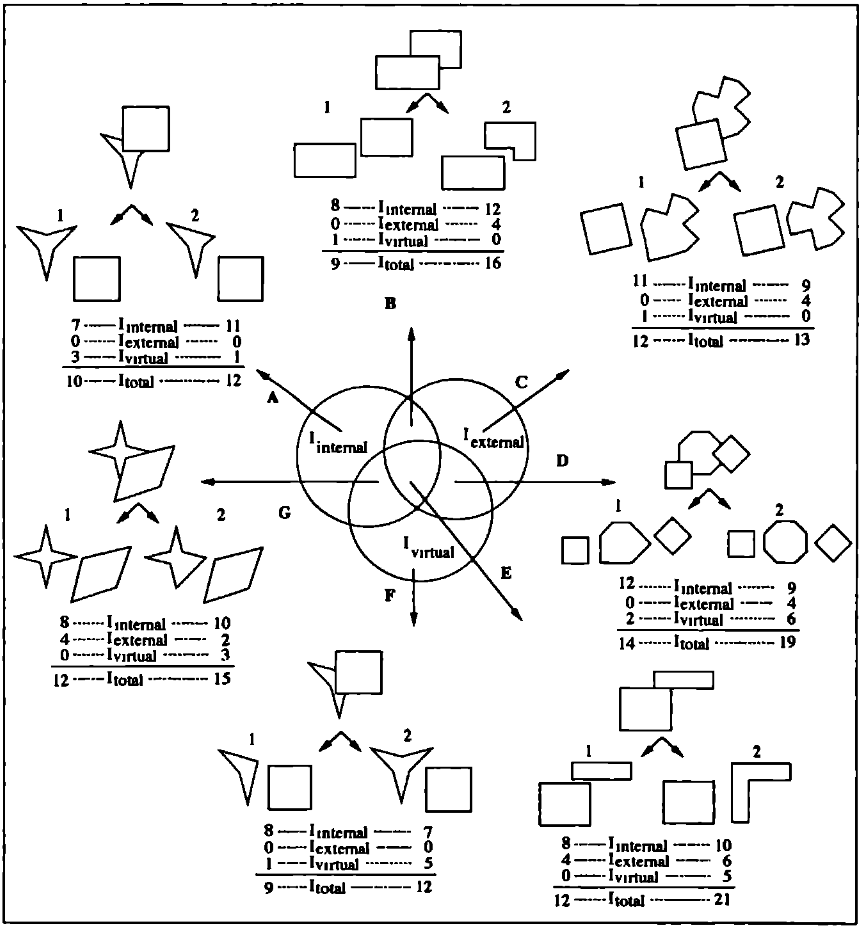


Figure 19. From each area in the Venn diagram shown in Figure 18, a pattern is depicted with two possible interpretations. The interpretations labelled with number 1 represent the most preferred interpretation of the pattern. Below each interpretation its complexities are given.

separately (52%, 65%, and 49%, respectively), it can be deduced that there is about equal tendency towards interpretations with either the simplest shapes, or the lowest degree of coincidence, or the lowest number of virtual elements. The Venn diagram in Figure 18 offers the opportunity to classify patterns according to the predictive quality of those three completion tendencies. In Figure 19, a pattern is depicted from every field in the Venn diagram.

Both for the most preferred interpretation and for the second-best interpretation, the complexity of each structure is given. For instance, in Figure 19 pattern A, $I_{internal}$ alone already predicts the most preferred interpretation correctly, which illustrates the simplest-shape tendency. For other patterns, for instance pattern D in Figure 19, introduced by Kanizsa (1985), $I_{internal}$ predicts wrongly whereas both $I_{external}$ and $I_{virtual}$ predict correctly. So, for each of the three completion tendencies, there is a restricted class of patterns for which that tendency alone can be considered to be decisive. The three tendencies correspond, to a certain extent, to the principle of Prägnanz (taken as focusing on the simplicity of shapes), the coincidence-explanation principle, and the principle of good continuation, respectively. In the past, researchers have sought for support for either this principle or that principle. In the present study, however, we have shown not only that three corresponding tendencies are about equally effective, but also that these tendencies can be integrated into one tendency (towards a minimal I_{total}) which is much more effective than each of the three tendencies separately.

Although the proportion of correct predictions on the basis of I_{total} is high, it is expedient to take a closer look at the patterns for which I_{total} leads to a wrong prediction. These wrong predictions seem to be caused by the fact that either $I_{external}$ or $I_{virtual}$ is overestimated. In Figure 20A, an example of the first category is given. Although, for the pattern in Figure 20A, I_{total} is the same for both interpretations, the mosaic interpretation is highly preferred to the occlusion interpretation. This pattern (Figure 20A) is taken from the set of Boselie and Wouterlood (1989). In their study, a

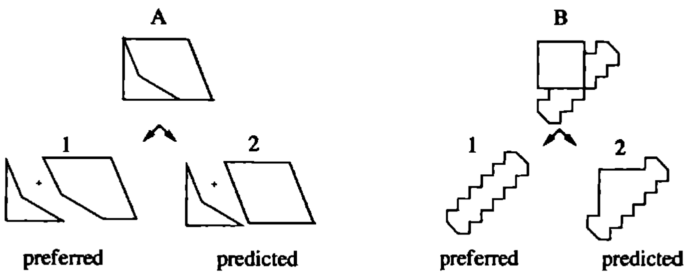


Figure 20. Two patterns, (A) and (B), for which the most preferred interpretation is not predicted correctly by the total perceptual complexity.

mosaic interpretation was assumed whenever subjects did not respond with an occlusion interpretation. We question, however, whether this assumption is justified. Another interpretation is possible and has already been proposed by Kopfermann (1930). In Figure 21 a more general pattern of the same type is depicted. This pattern is not easily interpreted as one shape occluding another. A mosaic interpretation with two adjacent shapes is shown as interpretation A. Interpretation B in Figure 21 reflects a completely different concept; one where the global contour or envelope plays an important role - a rectangle with a zigzag line in it. In this, the internal structure is determined by the shape of the envelope and the shape of the zigzag. Now, the perceptual complexity of the external structure is determined by the position of the zigzag with respect to the envelope. The perceptual complexities of the external structure of interpretations A and B are 8 and 2, respectively. Indeed, collinearity enhances the binding between pattern parts and leads, in this case, to an interpretation in which the global contour dominates. This illustrates that envelope interpretations may play a competitive role. However, more detailed research has to be focused on this type of interpretation and we will not consider these interpretations in our analysis.

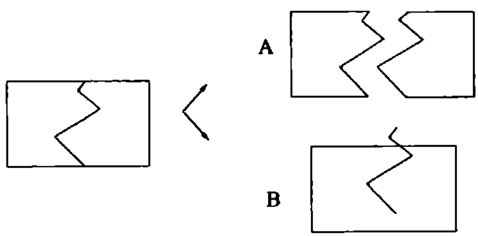


Figure 21. A and B represent two different interpretations of the pattern on the left. Interpretation A is a mosaic interpretation in which two separate shapes are juxtaposed. Interpretation B represents an interpretation in which the envelope of the pattern is taken as one shape. The zigzag as such is taken as a second shape.

A pattern belonging to the second category, in which $I_{virtual}$ seems to need adjustment, is depicted in Figure 20B, stemming from Buffart et al. (1981). The total perceptual complexity for the most preferred interpretation (B1) is higher than for the alternative interpretation (B2), mainly due to the high number of virtual elements in interpretation B1. A reasonable option is that, in addition to the number of virtual elements, the regularity within the virtual structure also plays a role. In order to account for this regularity, one could consider redundancy metrics that are in line with the redundancy concept of Attneave (1954) or with the weight-of-evidence concept of Mackay (1969). Our tentative view, however, is that it is not just the redundancy in the virtual structure that plays a role, but rather an interaction of the redundancies in the virtual structure and in the internal structure. Indeed, the higher the frequency of certain regular substructures in the total pattern, the more likely a completion with this specific regular structure will be made. Any appropriate specification of this type of redundancy requires more research and lies outside the scope of this study.

A further remark on the proposed complexity measure is that the summation of $I_{internal}$, $I_{external}$ and $I_{virtual}$ is but one of the possible combinations. Other relations between the complexities could be proposed, eventually including weighing factors for a specific type of complexity. Given the present results, however, we conclude that a simple summation already yields a good indicator for the perceptual complexity of an interpretation.

Summarizing, the main points in our approach are as follows: i) A distinction is made between memory complexity and perceptual complexity. That is, it is not the relation between interpretation and memory storage which is relevant, as often has been assumed, but the relation between interpretation and pattern. ii) This distinction has a great impact on dealing with coincidences caused by the positional relation between the shapes in an interpretation. Although coincidences decrease the memory complexity, they increase the perceptual complexity, not because they are improbable but because they reflect regularities in the external structure of an interpretation. iii) The perceptual complexity of the internal, the external, and the virtual structure of an interpretation are expressed in the same terms, namely in terms of structural information. In this way, three perceptually relevant tendencies can be combined and subjected to the minimum principle, thereby establishing an integration of global and local aspects of visual occlusion.

"Diversity by Simplicity"

Chapter 3

Competing global and local completions in visual occlusion

Abstract
In visual occlusion two amodal-completion tendencies occur frequently. One tendency leads toward the simplest completed shape (a global completion) and the other to a shape for which the completion itself is as simple as possible (a local completion). Two experimental paradigms were used to test the strengths of these completion tendencies: a drawing task and a simultaneous-matching task. The experimental results support the notion that the preference for either a global or a local completion is the consequence of a competition between interpretations. Finally, the authors discuss how the preference for a completion can be predicted by a model that is based on a quantification of both global and local aspects.

1 Introduction

Objects might be positioned such that one object partly occludes another object. In many cases it appears that the visible part of the occluded shape is perceptually completed. This phenomenon has been referred to as amodal completion because the subjective presence of the occluded part of an object emerges without any modal characteristics (cf. Kanizsa & Gerbino, 1982; Kanizsa, 1985; Gerbino & Salmaso, 1987). During past decades several studies on visual occlusion and amodal completion have been done by various researchers (cf. Chapanis & McCleary, 1953; Dinnerstein & Wertheimer, 1957; Buffart, Leeuwenberg, & Restle, 1982; Kanizsa & Gerbino, 1982; Gerbino & Salmaso, 1987; Boselie, 1988; Boselie & Wouterlood, 1989; Kellman & Shipley, 1991; Sekuler & Palmer, 1992; Wouterlood & Boselie, 1992; Van Lier, Van der Helm, & Leeuwenberg, 1994). In the literature two types of amodal completion are frequently described: According to a global completion, the completed shape is as simple as possible, and according to a local completion, the completion itself is as simple as possible. In Figure 1 two different completions of a pattern are given. Figure 1A shows the global shape, that is, the shape resulting from the global completion. Figure 1B shows the local shape, that is, the shape resulting from the local completion.

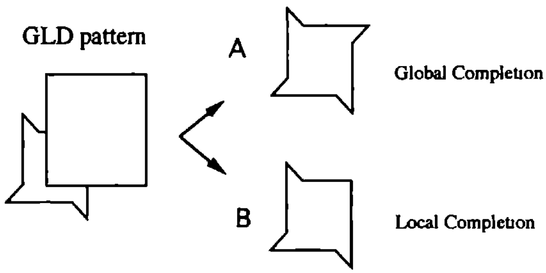


Figure 1. Two possible occlusion interpretations of the same pattern. Interpretation A represents the simplest global completion and interpretation B the simplest local completion. Because global and local completions of the pattern diverge into different shapes, the pattern is referred to as a GLD pattern (Global-Local-Divergent).

In the remainder of this article we call patterns like that in Figure 1 GLD patterns (Global-Local-Divergent) because global and local completions of such a pattern yield different shapes. This contrasts with GLC patterns (Global-Local-Convergent) for which global and local completions yield the same shape (see Figure 2). (Of course, still other, more complex completions are possible, like shape B in Figure 2, but we do not consider them because they are hardly perceptually relevant.)

It is important to realize that the exact shape that is called global or local depends on the employed notion of global and local simplicity. Consequently, the GLC/GLD classification made above also depends on the employed notion of simplicity.

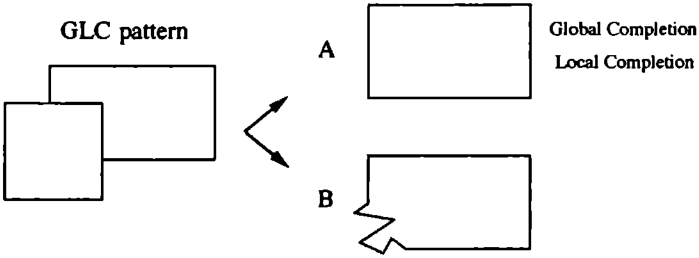


Figure 2. Two possible occlusion interpretations of the same pattern. Interpretation A represents both the simplest global and the simplest local completion. Because global and local completions converge to the same shape, the pattern is referred to as a GLC pattern (Global-Local-Convergent). Other, more complex, interpretations, like Interpretation B, are also possible but are hardly perceptually relevant.

Theories that emphasize local simplicity bear heavily on the role of the Gestalt principle of good continuation in pattern completion. In this article we assume that, according to this principle, a local completion is constituted by a *linear* continuation of the visible contours of the background shape behind the occluding shape, as shown in Figures 1B and 2A. Other operationalizations of the good-continuation principle are also possible. Kellman and Shipley (1991) argued that a completion will be such that points of occlusion are connected by the simplest continuous function. However, the generalizability of this assumption has been criticized by Boselie and Wouterlood (1992), who mentioned several limitations of the hypothesis of Kellman and Shipley. Nevertheless, Wouterlood and Boselie (1992) presented a local-completion theory that is based on the good-continuation principle as well. The application of this principle in combination with predefined junction types, which might occur between two surfaces, enables them to predict when occlusion is experienced. Whenever an occlusion occurs, the visible part of the background shape is completed by means of linear good continuation. However, up until now their theory is restricted to configurations of two completely irregular surfaces. As Wouterlood and Boselie themselves already indicated, this restriction implies that typical global characteristics of patterns are ignored.

In contrast with local theories, global theories take into account all regularities within a pattern. Early Gestalt psychologists (Köhler, 1947; Wertheimer, 1923) discussed already the relevance of regularities for visual perception. The Gestalt law of Prägnanz (Koffka, 1935) embodies the concept that perception tends to result in overall simplicity. This Gestalt law can be regarded as the predecessor of the global-minimum principle. The global-minimum principle (Hochberg & McAlister, 1953) conjoined with a descriptive system of visual patterns (cf. Hochberg & McAlister, 1953; Leeuwenberg, 1969, 1971; Restle, 1982) results in clear predictions of the preferred pattern interpretations. The encoding of patterns may proceed in various ways. For the moment, we assume the application of the minimum principle in visual occlusion to be such that the simplest shape, according to a specific coding scheme, is predicted to be preferred. Following the coding procedure within Structural Information Theory (SIT) (Van der Helm & Leeuwenberg, 1991), the shapes in Figures 1A and 2A indeed appear to be the simplest for the given patterns. (The coding rules and the encoding procedure are briefly discussed in the Appendix.) However, the global-minimum principle has been criticized too by several researchers who demonstrated that the preferred interpretation does not always coincide with the interpretation with the simplest shape (cf. Kanizsa, 1985; Rock, 1983; Boselie, 1988). The pattern given in Figure 3 was brought in by Kanizsa (1985). Interpretation A in Figure 3 is supposed to agree with the global-minimum principle, yet interpretation B generally is preferred to A.

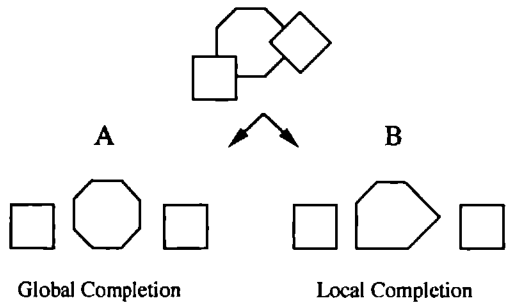


Figure 3. A GLD pattern adopted from Kanizsa (1985). Interpretation A represents the global completion and interpretation B the local completion. The local completion appears to be more prevalent than the global completion.

The majority of arguments of proponents or opponents of a given theory in this global-local discussion on visual completion comprises phenomenal examples and counterexamples for one or the other theory. Apparently, in some cases the perceptual process results in an interpretation that can be classified as a global completion, whereas in other cases a local completion is more prevalent. Given this fact, a theory that is strictly based on either global simplicity or local simplicity cannot hold. In our view a theory of visual completion has to incorporate both global and local aspects of pattern interpretations. In this article we discuss two questions:

a) Can the preferred completion be conceived as the result of a competition between global and local completions?

b) How can global and local aspects be accounted for in the selection of an interpretation?

Before we deal with these questions, we first present an introductory experiment that demonstrates the relevance of both global and local completions.

2 Experiment 1: Both global and local completions are relevant.

2.1 *Subjects*

Twenty-one undergraduate students served as participants. All participants received course credit.

2.2 *Stimuli*

The stimulus set consisted of the GLD patterns given in Figure 4.

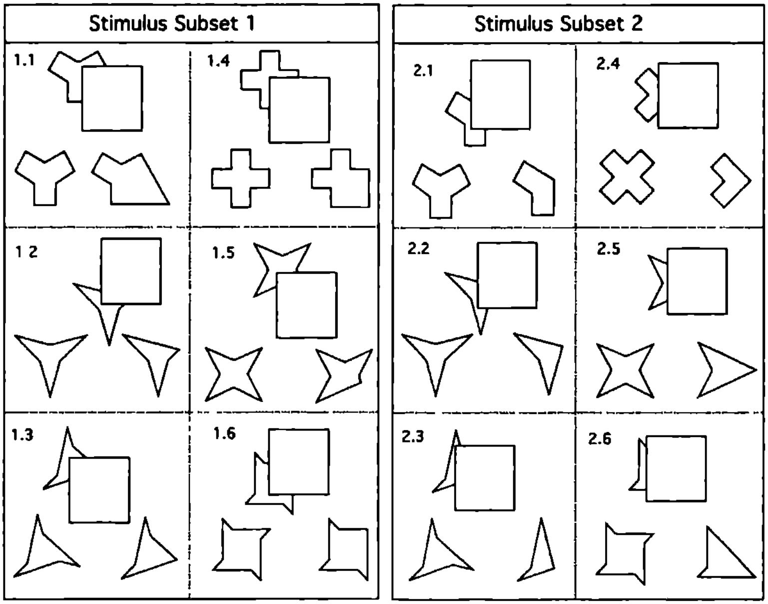


Figure 4. The patterns used in Experiment 1. All patterns are GLD patterns. For each pattern the global completion is drawn on the left and the local completion is drawn on the right.

The construction of these patterns started with one of six symmetrical shapes, containing mirror symmetry (with three or four axes of symmetry) or rotation symmetry. Each symmetrical shape was partly occluded by a rectangle, such that they constituted a GLD pattern. The global completion of each GLD pattern resulted in the symmetrical shape, whereas the local completion was reached by linear good continuation of the visible part of the occluded shapes. Two stimulus subsets were designed. Within stimulus subset 1 a relatively small part of the symmetrical shape was occluded, whereas within stimulus subset 2 a relatively large part of the symmetrical shape was occluded. As a consequence of this procedure, the global shape was the same in both stimulus subsets, whereas the local shape varied between the stimulus subsets. For reasons of comparability with Experiment 2B, the relative orientation of each shape with respect to the occluding rectangle was such that the rectangle had the same (upright) position for all patterns. Pattern height was between 3 cm and 5 cm.

The main goal of the manipulation described above was the creation of a set of patterns in which the preference for a specific global completion could be tested for two patterns with different local completions.

2.3 *Procedure*

The patterns were presented in random order on pieces of paper. The orientation of each pattern was as given in Figure 4. The participants were told that every drawing represented two surfaces: a rectangle and a shape behind the rectangle. The participants were asked to draw the contours of the occluded part of the perceived background shape for each pattern.

2.4 *Results*

Within stimulus subset 1, global completions were preferred in 81% of all cases and local completions in 13% of all cases. Within stimulus subset 2, global completions were preferred in 28% of all cases and local completions in 64% of all cases. The percentages of global and local completions do not sum up to 100% exactly, because some completions did not fit the present definition of global or local completion. In Table 1 the proportion of preference for the global completion is presented for each pattern. This proportion ($Pref_{GIL}$) is calculated by the number of participants (N) who preferred the global completion divided by the number of participants who preferred either the global or the local completion: $Pref_{GIL} = N_{global} / (N_{global} + N_{local})$.

Pattern	$Pref_{GIL}$	Pattern	$Pref_{GIL}$
1.1	0.95	2.1	0.35
1.2	0.86	2.2	0.33
1.3	0.50	2.3	0.24
1.4	0.95	2.4	0.38
1.5	1.00	2.5	0.30
1.6	0.85	2.6	0.22

Table 1. Experiment 1 (drawing task): relative preference for each GLD pattern. $Pref_{GIL}$ = number of global completions / (number of global completions + number of local completions).

2.5 *Discussion*

The data clearly illustrate that both global and local completions are relevant in pattern completion. The manipulation for generating both stimulus subsets may have affected several factors that caused the overall shift in preference from global completions in stimulus subset 1 to local completions in stimulus subset 2. Later in this article we deal with the question of which factors may be responsible for the preference for either a global or a local completion. For the moment we maintain our statement that any theory on pattern completion that emphasizes either global simplicity or local simplicity fails. We now turn to the first question.

3 Question 1: Can the preferred completion be conceived as the result of a competition?

The competition between alternative interpretations is not an obvious fact, at least according to various perceptual theories. Perceptual models that aim at a minimization of process, such as a hill-climbing procedure (Attneave, 1982), typically result in only one interpretation. Also, theories in which local cues such as junction types (cf. Barrow & Tenenbaum, 1981; Wouterlood & Boselie, 1992) or nonaccidental properties (Biederman, 1987) play a dominant role, lead in principle to just one interpretation. In some cases conflicting cues may lead to a predicted ambiguity (cf. Wouterlood & Boselie, 1992), but this does not imply the assumption of a competition between different interpretations for nonambiguous patterns. In contrast with this, perceptual theories that use a selection criterion for the perceived interpretation use the idea of more possible candidates. Both the likelihood principle (cf. Von Helmholtz, 1867/1962) and the minimum principle (Hochberg & McAlister, 1953; see also Hatfield & Epstein, 1985) can be conceived as such. Already Herbart (1850) proposed that the degree in which one interpretation prevails over another is the result of a competition between different interpretations. Mens and Leeuwenberg (1988) resumed two basic ideas in Herbart's theorizing: (a) the conscious percept is but one out of many subliminal candidates, and (b) the dominant percept may vary in strength, depending on the attractiveness of the competing interpretations. In addition, Mens and Leeuwenberg demonstrated the hidden presence of alternative interpretations for certain visual patterns.

In line with the latter ideas, the competition between global and local completions may gain support by a possible interdependency of the strengths of both types of completions. In the following experiments this interdependency is tested by means of the simultaneous-matching task (Gerbino & Salmaso, 1987).

3.1 *Simultaneous-matching task*

We first review parts of the study by Gerbino and Salmaso (1987). Consider Figure 5. In one of their experiments, patterns like A and B were presented simultaneously with shapes such as C or D. Participants were asked to indicate as quickly as possible whether the simultaneously presented single shape was present in the pattern. It appeared that positive responses on the presence of shape C in pattern A required about the same reaction times as did the positive responses on the presence of the same shape in pattern B. Furthermore, positive responses on the presence of shape D in pattern B required significantly longer reaction times than did positive responses on the presence of shape C in pattern B.

Gerbino and Salmaso (1987) concluded that amodally completed shapes are functionally equivalent to complete shapes. Gerbino and Salmaso further remarked that their experiments were not designed to test whether completion tends to be global or local. Indeed, their stimulus set consisted of GLC patterns, so that both global and local completion strategies converged to the same completed shape. In case of GLD patterns, however, the response times on global and local completions may be influenced by their relative strengths.

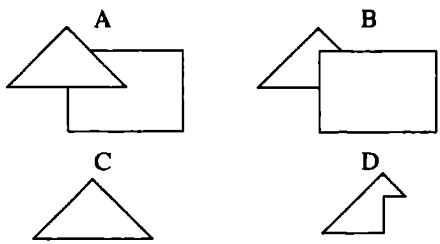


Figure 5. According to Gerbino and Salmaso (1987) the recognition of shape C in pattern A occurs within the same time span as the recognition of shape C in pattern B. Moreover, in pattern B, shape C is recognized more rapidly than shape D.

3.2 *Experiment 2A (Pilot experiment)*

We adopted only part of the experimental procedure of Gerbino and Salmaso (1987). For this reason we first present a pilot experiment to examine whether the present procedure leads to the same results on GLC patterns as Gerbino and Salmaso found. We focus on the question of whether matching a shape with a partly occluded shape evokes the same response times as matching it with a completely visible shape.

3.2.1 Subjects

Twenty-two undergraduates participated in the experiment. All participants received course credit.

3.2.2 Stimuli and procedure

Like Gerbino and Salmaso (1987), we used line drawings. The complete stimulus set was based on six patterns and three target shapes (see Figure 6). In the following discussion we refer to this stimulus set as the GLC set. Each pattern consisted of a rectangle with a second shape positioned either behind or in front of that rectangle, which represented the occlusion condition and the no-occlusion condition, respectively. (Evidently the distinction occlusion/no-occlusion refers to the position of the nonrectangular shape.) In a stimulus presentation each pattern was paired with a target shape. This target shape either could be matched with the (nonrectangular) shape within the pattern or could not be matched with that shape. In this way a small set of twelve stimuli was constructed, for which the amounts of correct Yes and No answers were balanced. In Figure 7 a schematic presentation of the events in a trial is shown. At time T=0 a rectangle (1.5° wide) was presented in the upper half of a monitor screen. After 2 seconds an additional shape, shape A, appeared either in front of the rectangle (no-

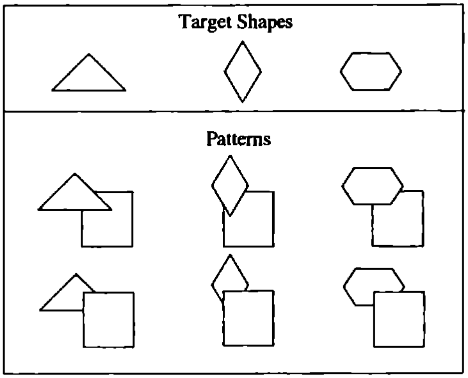


Figure 6. Target shapes and patterns as used in Experiment 2A.

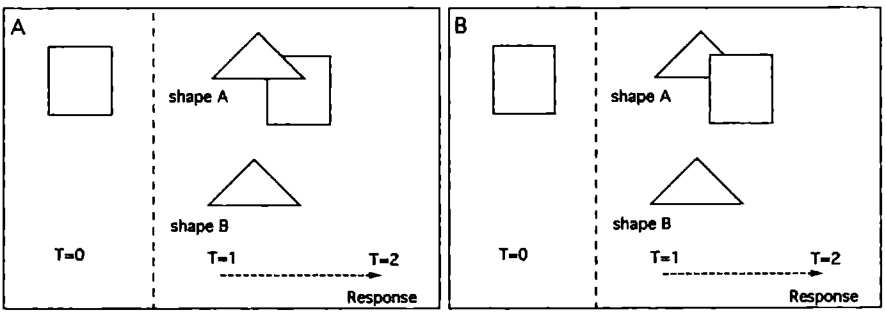


Figure 7. A schematic layout of the events in a stimulus presentation of Experiment 2. At T=0, a rectangle was presented. After 2 s (T=1) a shape (shape A) appeared either in front of the rectangle (see Figure 7A) or partly behind the rectangle (see Figure 7B). Also at T=1, a second shape (shape B) appeared. The participant had to verify whether shape B could be matched with shape A. Response times were measured, being the time from T=1 until a button (yes/no) was pressed (at T=2).

occlusion condition, see Figure 7A) or partly behind the rectangle (occlusion condition, see Figure 7B). At the same time, another shape, shape B, was presented in the lower half of the screen. The total visual angle was about 6°.

The task of the subject was to verify whether shape B could be matched with shape A. If shape A partly covered the rectangle (Figure 7A), the subject had to respond whether shape A and shape B were the same. If shape A was partly covered by the rectangle (Figure 7B), the subject had to respond whether shape A could be the same as shape B. Responses were given by pressing one of two buttons (yes or no). Participants were asked to respond as quickly as possible. The response time was measured, being the time from the appearance of shapes A and B until a button was pressed. The patterns remained on the screen until a response was given. Before running the experiment, the participants were trained on a set of stimuli different from the stimuli used in the experiment. During the training period, participants were given feedback on their responses. During the experiment, no feedback was given. The order of presentation of stimuli was randomized for each subject.

3.2.3 Results and discussion

The results are shown in Table 2. For each combination the mean response time for the correct answers, the standard error of the response times, and the percentage of incorrect answers (relative to the amount of stimuli per cell) are given. An analysis of variance (ANOVA) for repeated measurements on these data has been performed, revealing no main effect on Occlusion ($F(1,21)=0.55$, $p>0.10$). That is, the response time on matching a shape with a completely visible shape was not significantly different from the response time on matching it with a partly occluded shape. In concordance with the results of Gerbino and Salmaso (1987) there was a significant main effect on Match, $F(1,21)=8.41$, $p<0.01$. The Occlusion x Match interaction was not significant, $F(1,21)=0.38$, $p>0.10$. Finally, a t-test was performed on the responses for stimuli in which a match was possible, which revealed no significant effect for Occlusion ($t(21)=0.89$, $p>0.10$).

COMBINATION	RT(ms)	SE(ms)	ER(%)
Match / Occlusion	736.5	40.2	1.5
Match / No-Occlusion	712.5	27.1	1.5
No-Match / Occlusion	799.2	37.5	1.5
No-Match / No-Occlusion	799.3	44.2	3.0

Table 2. Experiment 2A (matching task): overall results on GLC patterns. RT = Response Time; SE = Standard Error; ER = Error Rate.

The results on the present experimental procedure confirm Gerbino and Salmaso's (1987) findings for GLC patterns. Therefore, we can now turn to the application of this procedure to GLD patterns.

3.3 *Experiment 2B*

3.3.1 Subjects

Thirty-one undergraduates participated in the experiment. All participants received course credit.

3.3.2 Stimuli and procedure

The same patterns as in Experiment 1, having the same orientations, were used. Each of the 12 GLD patterns of Experiment 1 led to 8 stimuli in the present experiment, so that in total there were 96 stimuli. An example is given in Figure 8. Every pattern-target combination in Figure 8 represents a stimulus as used in the experiment. Pattern D was added to the set of combinations to balance the amounts of correct Yes and No answers. In the following discussion we refer to this stimulus set as the GLD set. The stimulus presentation procedure was the same as in Experiment 2A.

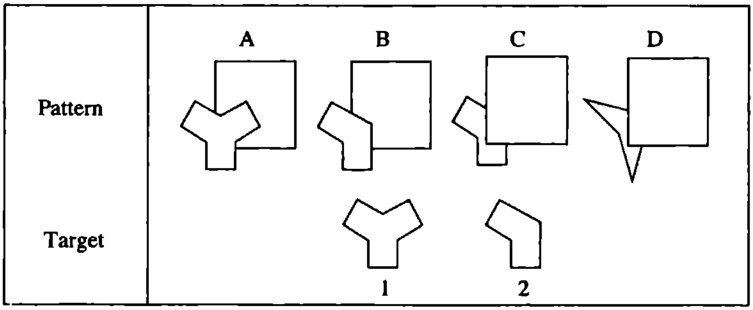


Figure 8. Each pattern-target combination represents a stimulus as used in Experiment 2B.

3.3.3 *Results and discussion*

In Table 3, overall data are presented. An ANOVA for repeated measurements on these data revealed a significant main effect on Occlusion, $F(1,30)=40.3$, $p<0.001$, a significant main effect on Match, ($F(1,30)=9.55$, $p<0.01$), and an Occlusion x Match interaction, $F(1,30)=63.8$, $p<0.001$.

To test the differences between the GLC set and the GLD set an ANOVA with Set (GLC vs. GLD) as a between-subjects variable was performed on the data of both Experiments 2A and 2B. There was a significant main effect on Set, ($F(1,51)=49.93$, $p<0.001$). There was no Match x Set interaction, $F(1,51)=0.05$, $p>0.10$, and a significant

COMBINATION	RT(ms)	SE(ms)	ER(%)
Match / Occlusion	1342.6	65.6	4.4
Match / No-Occlusion	1036.6	36.1	2.2
No-Match / Occlusion	1237.8	54.3	5.4
No-Match / No-Occlusion	1276.2	51.7	9.6

Table 3. Experiment 2B (matching task): overall results on GLD patterns. RT = Response Time; SE = Standard Error; ER = Error Rate.

Occlusion x Set interaction, $F(1,51)=18.17$, $p<0.001$. The threefold Occlusion x Match x Set interaction was also significant, $F(1,51)=27.5$, $p<0.001$.

The overall high response times on the GLD set, in comparison with those on the GLC set, can be explained by the fact that the shapes within the GLD set are more complex than those within the GLC set. Most important, however, is that, in case of a possible match, the GLC set yielded no significant difference between the occlusion condition and the no-occlusion condition, whereas the GLD set yielded significantly longer response times in the occlusion condition in comparison with the no-occlusion condition. In Figure 9 the response times on possible matches are depicted for both the GLC set and the GLD set.

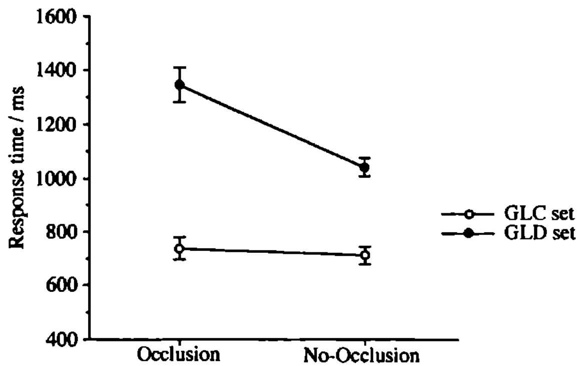


Figure 9. The response times (RT) on possible matches in the GLC set (Experiment 2A) and the GLD set (Experiment 2B).

We now focus on the responses on possible matches in the GLD set. The data are split up with respect to Stimulus Subset (see Table 4) and Type of Shape (global versus local). In Table 4 the mean response times are presented. Per participant, the response on a possible match in the occlusion condition and the response on a possible match in the no-occlusion condition, involving the same shape, were considered only if both responses were correct. This excludes 6% of all responses. In all cases the mean response times in the occlusion condition were higher than the mean response times in the no-occlusion condition. We performed t-tests on these differences, and they appeared to be highly significant ($p<0.001$, see also Table 4). For each shape representing a global or a local completion of a GLD pattern the difference in response time (DRT) between the no-occlusion condition and the occlusion condition was calculated within participants (see also Figure 10). An ANOVA for repeated measurements performed on these values revealed no significant main effect on Stimulus Subset, $F(1,30)=1.67$, $p>0.10$, a significant main effect on Type of Shape (global versus local), $F(1,30)=8.02$, $p<0.01$, and a significant Stimulus Subset x Type of Shape interaction, $F(1,30)=20.74$, $p<0.001$.

Type of Shape	Condition (ms)		DRT	t(30)
	Occlusion	No-Occlusion		
	Stimulus Subset 1			
global	1157.2	969.3	187.9	4.67
local	1621.3	1156.0	465.3	7.61
	Stimulus Subset 2			
global	1327.4	999.0	328.4	6.31
local	1249.5	1038.0	211.5	7.71

Table 4. Experiment 2B (matching task) mean response times on possible matches for GLD patterns. In all cases the response times in the occlusion condition are higher than the response times in the no-occlusion condition. In all cases the t-tests are highly significant ($p<0.001$). DRT = difference in response times

On the whole, the DRT values for the global shapes were the lowest for the patterns of stimulus subset 1, whereas the DRT values for the local shapes were the lowest for the patterns of stimulus subset 2. To relate the results of Experiment 1 with the results of Experiment 2B, we calculated for each pattern the mean DRT value of the global completion relative to the mean DRT values of both global and local completions. $DRT_{GIL} = DRT_{global} / (DRT_{global}+DRT_{local})$ (see Table 5). Correlating the

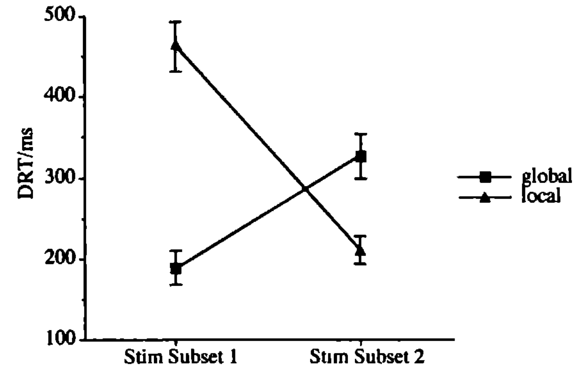


Figure 10. The mean difference in response times (DRT) values for possible matches in Experiment 2B are plotted for both stimulus subsets

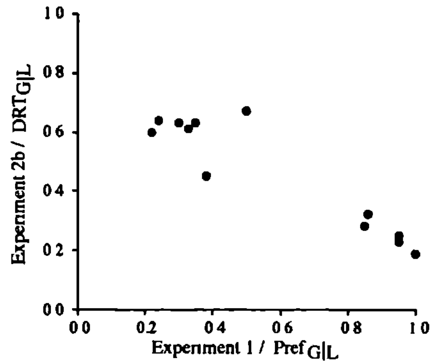


Figure 11. The results of Experiment 1 ($Pref_{G|L}$) are plotted against the results of Experiment 2B ($DRT_{G|L}$). Pref=preference; G=global, L=local; DRT=difference in response times.

proportion of preference, $Pref_{G|L}$, of Experiment 1 and the proportion $DRT_{G|L}$ of Experiment 2B, yields a Pearson's correlation coefficient of $r=-0.93$ ($p<0.001$) (see Figure 11). This indicates that, generally, the higher the preference for a completion is, the smaller the difference in response time between the occlusion condition and the no-occlusion condition will be.

The overall agreement between the results of both experiments indicates that the strength of the global completion depends on the strength of the local completion and vice versa. Note that from these experiments it cannot be deduced whether the different completions are concurrently present nor whether they are generated simultaneously or sequentially. The only argument here concerns the interdependency of the strengths of both types of completions. This interdependency supports the notion that the preference for either a global or a local completion is the result of a competition between those completions. We therefore pursue predictive models of pattern completion that account for that. This leads us to the second question.

Pattern	$DRT_{G|L}$	Pattern	$DRT_{G|L}$
1.1	0.23	2.1	0.63
1.2	0.32	2.2	0.61
1.3	0.67	2.3	0.64
1.4	0.25	2.4	0.45
1.5	0.19	2.5	0.63
1.6	0.28	2.6	0.60

Table 5. Experiment 2B (matching task): relative difference in response time for each GLD pattern. $DRT_{G|L}$ = DRT global completion / (DRT global completion + DRT local completion).

4 Question 2: How can global and local aspects be accounted for in the selection of an interpretation?

Given the above results, it is clear that any model on pattern completion has to deal with both global and local completions. We first evaluate some factors inherent to two-dimensional patterns that might have influenced the preference for a specific completion. After this we focus on a relatively simple model for pattern completion.

4.1 *Some factors in pattern completion*

4.1.1 Pattern orientation

Effects of orientation on pattern completion have been reported by Boselie (1988). More specifically, Boselie reported a preference for local completions with a vertical axis of symmetry. The vertical axis appeared not to be a dominant factor with respect to the global completions. Also from the data of Experiment 1 it is clear that a vertical axis of symmetry is not a dominant factor. For example, patterns 2.1, 2.2, 2.4, and 2.5 all had a vertical axis of symmetry for the global shape only. Nevertheless, the local completion was preferred.

4.1.2 Relative orientation of edges

Kellman and Shipley (1991) and Shipley and Kellman (1992) reported an effect of the relative orientation of edges on perceived occlusion. According to their relatability criterion, edges are relatable when linear extensions of occluded edges meet at obtuse angles or, as a limit case, at an angle of 90° (referred to as marginally relatable edges). According to their hypothesis, edges that meet with an angle less than 90° do not give rise to edge interpolation. If relative orientation of edges, expressed in terms of relatability, is taken as the only decisive variable with respect to the occurrence of a local completion, it is unclear, for example, why patterns 1.4, 1.5, and 1.6, having marginally relatable edges, lead to a global completion.

4.1.3 Familiarity

According to Peterson and Hochberg (1989), interpretations that represent familiar figures are more likely to be preferred. Also Kellman and Shipley's (1991) notions on preferred completions in case of nonrelatable edges depend on familiarity. Others are critical on the role of familiarity in pattern completion (cf. Kanizsa & Gerbino, 1982; Kanizsa, 1985). It is not always clear which predictions are made on the basis of this principle, as it lacks any quantification. In many cases the most regular shapes will be more familiar. Clearly, the overall responses on stimulus subset 2 contradict a tendency toward regularity. Familiarity obviously comprises more than regularity. Nevertheless, it cannot be the only crucial variable because many patterns, such as those in Wouterlood and Boselie (1992), yield strong preferences for unfamiliar completions.

4.1.4 Context

Somewhat related to the effects of familiarity are effects of context. The presence of other shapes in the visual field, with either spatial or temporal distance, could influence the preference for a certain interpretation (cf. Rock, 1985; Leeuwenberg, Mens, & Calis, 1985). With respect to both Experiments 1 and 2B, the appearance of other regular shapes might have biased the result toward a higher preference for regular completions.

4.1.5 Coincidence

Rock (1983) argued that the perceptual system avoids coincidences within interpretations. In case of occlusion patterns, these coincidences may occur between the contours of the shapes. Rock, however, did not give a metric of coincidence, so it is difficult to make precise predictions on the basis of this principle as such. All of our experimental patterns were constructed such that both global and local completions did not yield coinciding contours. Because of the fact that coincidences can be regarded as unexplained regularities (Rock, 1983), we argued elsewhere that coincidence can be expressed in terms of a quantifiable complexity (Van Lier et al., 1994). Also according, to that proposed quantification, both types of completions do not yield any coincidence. We conclude that the shift in preferences from global completions (stimulus subset 1) to local completions (stimulus subset 2) was not caused by a variation in coincidence.

4.1.6 Local configurations

Somewhat related to the effects of coincidence are the effects of local configurations. For instance, whether a completion occurs and, if so, which completion occurs may depend on the type of junctions at the points of occlusion (cf. Ratoosh, 1949; Wouterlood & Boselie, 1992). All of our experimental patterns were constructed such that T-junctions arose at all points of occlusion. Therefore, a variation in type of junctions at points of occlusion cannot have caused the shift in preferences.

4.1.7 Simplicity of shape

The complexities of the global and local shapes in terms of structural information (I) have been determined for each pattern. In the Appendix, the determination of I is shown for pattern 2.2. In Table 6, the I values are given for each pattern of Figure 4. It appears that for all patterns the global shape is simpler than the local shape. So, if there is a dominant tendency toward the simplest shape, the global shape should be perceived for all patterns drawn in Figure 4. Clearly, the preferences on the patterns of stimulus subset 2 are in contradiction with this idea. One might argue that the local shapes of stimulus subset 2 are simpler than those of stimulus subset 1 and that this might have caused the shift to local completions in stimulus subset 2. For example, there are more local shapes in stimulus subset 2 that have an axis of symmetry. Consequently, the difference in complexity between global and local shapes is smaller for stimulus subset 2. However, the local shapes are still more complex than the global shapes and therefore will not be predicted on the basis of simplicity of shape. Moreover, given the information loads, the difference in complexity cannot be a factor with a strong predictive power because it is not clear what the absolute value of this difference has to be in order to reach the shift in completion. For instance, the difference in complexity (in terms of structural information) between the global and the local shapes for pattern 1.4 and pattern 2.3 is exactly the same for both patterns, yet for pattern 1.4 the global completion is preferred, whereas for pattern 2.3 the local completion is preferred.

None of the above factors alone can account for the preferences for either a global or a local completion. The list of discussed factors certainly is not exhaustive. Other factors, such as the lengths of edges at points of occlusion or the occluded area, might affect completion as well. An all-embracing model for the prediction of pattern completions has to deal with all possible factors. In the discussion below, however, we propose a relatively simple model on pattern completion, which is based only on the simplicity of the completed shape and the simplicity of the amodal part of that shape. Before that, we present a replication of Experiment 1 to control for two aspects that might have influenced the outcome of Experiments 1 and 2B, namely orientation and context. These aspects can be controlled without changing the patterns themselves.

Pattern	Global			Local			Pattern	Global			Local		
	I	V	V'	I	V	V'		I	V	V'	I	V	V'
1.1	5	5	3	6	1	1	2.1	5	7	4	6	1	1
1.2	4	3	3	8	1	1	2.2	4	5	3	5	1	1
1.3	5	3	3	8	1	1	2.3	5	5	5	8	1	1
1.4	5	5	3	8	1	1	2.4	5	13	5	6	1	1
1.5	4	3	3	9	1	1	2.5	4	9	4	5	1	1
1.6	5	3	3	9	1	1	2.6	5	9	6	8	1	1

Table 6. Complexities for the global and local completion of each GLD pattern. The complexity of the completed shape is given by I. The complexity of the amodal part of that shape is given by V and V', which represent two different quantifications.

4.2 *Experiment 3 (Replication of Experiment 1)*

4.2.1 Subjects

Two hundred eighty-eight undergraduate students participated voluntarily.

4.2.2 Stimuli

The same patterns as in Experiment 1 were used. To reduce effects of orientation, each pattern was presented in 24 orientations, with steps of 15 degrees, starting with the orientation given in Figure 4. In total there were 12*24=288 stimuli. The stimuli were drawn on pieces of paper.

4.2.3 Procedure

Each subject received only one stimulus. This was done to eliminate context effects of other stimuli. The instruction was the same as in Experiment 1. Again the participants were asked to draw the contours of the occluded part of the perceived background shape.

4.2.4 Results

Within stimulus subset 1, global completions were preferred in 69% of all cases and local completions in 22% of all cases. Within stimulus subset 2, global completions were preferred in 15% of all cases and local completions in 78% of all cases. In Table 7 the proportion of preference for the global completion is presented for each pattern. Note that, in comparison with Experiment 1, pattern 1.1 shows a remarkable switch from a global to a local completion. For the other patterns the proportions generally are more extreme than in Experiment 1, especially for patterns 2.1, 2.2, and 2.3.

Pattern	$Pref_{G/L}$	Pattern	$Pref_{G/L}$
1.1	0.29	2.1	0.13
1.2	0.90	2.2	0.17
1.3	0.43	2.3	0.00
1.4	1.00	2.4	0.39
1.5	0.96	2.5	0.17
1.6	0.90	2.6	0.10

Table 7. Experiment 3 (drawing task): replication of Experiment 1 but controlling for orientation and context for each GLD pattern. $Pref_{G/L}$ = number of global completions / (number of global completions + number of local completions).

4.3 *A simple completion model*

We start with the observation that in pattern completion there are two opposing tendencies. On the one hand, there is a tendency toward a global completion, which is characterized by an overall simplicity of the completed (background) shape but which may result in a rather complex amodal part of that shape. On the other hand, there is a tendency toward a local completion, which is characterized by a relatively simple amodal part of a shape but which may result in a more complex completed shape than under global completion. To deal with these opposing tendencies, we consider the perceptual complexity of an interpretation based on the complexity of both the completed shape and the amodal part of that shape. The complexity of the completed shape (global or local) has already been dealt with. To define the complexity of the amodal part of a shape we follow a proposal that has been made in Van Lier et al. (1994). In that study we argued that the number of occluded, or "virtual", contour elements already provides a solid basis for an operationalization of the perceptual complexity of the amodal part. We refer to the complexity of the amodal part with V. In the Appendix the determination of V is shown for pattern 2.2. In Table 6 the V values for all experimental patterns are given. Now, within the proposed model every interpretation, whether global or local, is treated equally with respect to the determination of its perceptual complexity. That is, both the complexity of the completed shape and the complexity of the amodal part of that shape are assumed to contribute to the perceptual complexity of an interpretation. We propose to quantify the perceptual complexity (P) of an interpretation by a simple summation of those two complexities: P=I+V.

We hypothesize that P is the lowest for the most preferred interpretation. To give an example, we apply this to the completions of pattern 2.2. The perceptual complexities of the global and the local completions are P_{global}=P(A)=I(A)+V(A)=9 and

P_{local}=P(B)=I(B)+V(B)=6, respectively. Because P(B)<P(A), shape B is predicted to be preferred. If the perceptual complexity (P) is used as a predictor for the data of Experiment 3, it appears that, for 10 out of 12 patterns, the most preferred interpretation bears the lowest perceptual complexity. The correlation coefficient of the proportion of preference for the global completion ($Pref_{G|L}$) with the corresponding proportion of the perceptual complexities $P_{G|L}=P_{global}/(P_{global}+P_{local})$ is r=-0.69. (p<0.01). Note that the proportion of the theoretical perceptual complexities expresses the strength of the global completion relative to the local completion.

To complete this analysis, the theoretical complexity of the amodal part is modified by extracting redundancy from the series of virtual elements by means of encoding, in the same way as has been done for the completed shapes. We refer to this measure with V'. Notice that for every occluded shape, V' is always equal to, or smaller than, V. (In the Appendix, this is shown for pattern 2.2., and in Table 6 the V' values for all experimental patterns are given.) Now, the perceptual complexity of each interpretation is taken to be P'=I+V'. Applying this to the completions of pattern 2.2, the values of the perceptual complexities are P'_{global}=P'(A)=I(A)+V'(A)=7 and P'_{local}=P'(B)=I(B)+V'(B)=6. Note that P'(A) is closer to P'(B) than P(A) and P(B) were in the previous proposal, but again shape B is predicted to be preferred. Testing the perceptual complexity P' on the data reveals 11 out of 12 patterns for which the most preferred completion has the lowest perceptual complexity. The correlation coefficient of $Pref_{G|L}$ with the proportion of the perceptual complexities $P'_{G|L}$ is r=-0.84 (p<0.001).

The above analysis shows that a combination of just two structurally describable factors already predicts the data reasonably well. Within the present model, the quantification of global and local aspects proceeds within the same quantifying scheme. The proposed model can easily be expanded with other factors that can be expressed in terms of structural information. Such a factor is the coincidence between contours of the shapes. Consider for example Figure 12. For both patterns A and B the global completion results in the same regular octagon. The local completion is also the same for both patterns. Note, however, that for pattern A the corners of the octagon coincide with the contours of the occluding square. Clearly, in this pattern the tendency to a global completion appears to be weaker (and the tendency to a local completion stronger) than in pattern B. This type of coincidence can be conceived as a regularity between the shapes and can be described structurally. We argued elsewhere (Van Lier et al., 1994) that such coincidences increase the perceptual complexity of an interpretation. As mentioned already, in the present patterns such coincidences were avoided and therefore did not add to the perceptual complexity of global and local shapes as defined within the model.

The main characteristic of the presented model is that each interpretation is evaluated in the same way on both global and local aspects by means of a quantification of these structurally describable aspects. Other aspects, however, such as orientation of shapes, the relative orientation of edges, or familiarity, cannot be described structurally so far. Some of these aspects could in principle be implemented in a predictive model by assigning weighing factors to the perceptual complexities of different types of completions. However, the magnitudes of such weighing factors will have to be determined experimentally and will not be a consequence of our theory.

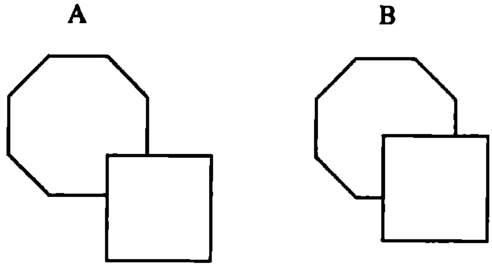


Figure 12. For both patterns A and B the global completion results in the same regular octagon. The local completion is also the same for both patterns. In pattern A the corners of the octagon coincide with the contours of the occluding square. In this pattern the tendency to a global completion appears to be weaker (and the tendency to a local completion stronger) than in pattern B.

6 General discussion and conclusion

In concordance with various researchers (cf. Herbart, 1850; Gregory & Gombrich, 1973; Leeuwenberg & Buffart, 1983) we consider the selection of an interpretation as the result of a competition between various interpretations. The existence of a theoretical measure that provides a high correlation between the ratio of theoretical complexities of alternative interpretations and the ratio of the actual preferences supports such a competition.

One question that may arise is which completions are actually competing? It seems implausible that the perceptual system generates all possible completions. This would mean, for example, that interpretation B in Figure 2 is also generated. The amount of different completions therefore will be innumerable. We do not think that the perceptual process actually generates all possible completions. In our view the generation of completions is constrained such that only "compatible extensions" of the visible structure are produced. We leave exact definitions of these compatible extensions for a forthcoming study but give here a rough sketch of the idea.

The pattern in Figure 13 can easily be interpreted as a rectangle occluding a wirelike shape. Roughly speaking, a compatible extension repeats parts of the visible structure. In Figure 13, completion A repeats a small line segment of the line that disappears behind the occluding surface. Completion B repeats a larger part of the visible structure, whereas completion C repeats the whole visible structure. Completions D and E cannot be conceived as repetitions of visible parts. Therefore, they are not compatible extensions and should be excluded a priori. With respect to virtual angles, compatible extensions need a further specification: All angles formed by at least one virtual line should be repetitions of angles within the visible part. Consider again Figure 1. All virtual angles of the global completion (shape A) are connected by at least one virtual line. In this case, each virtual angle indeed is a repetition of a visible angle. The local completion (shape B in Figure 1) introduces an angle that cannot be conceived as a repetition of a visible angle. However, in this case the virtual angle results from a continuation. According to our definition of virtual lines, the virtual angle is not connected with virtual lines and therefore still is a compatible extension. We call the described restriction on extensions the *compatibility of elements.*

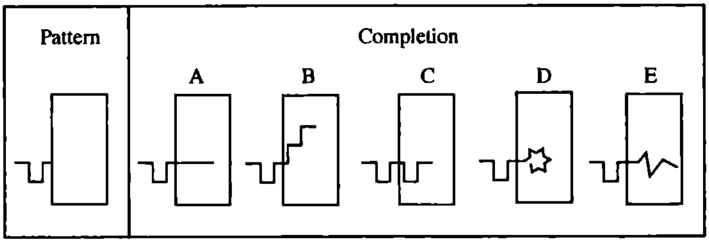


Figure 13. The pattern can easily be interpreted as a rectangle occluding a wirelike shape. Completions A, B, and C all represent compatible extensions of the visible structure, because they all repeat parts of the visible structure. Completions D and E cannot be conceived in that way.

It is evident that a repetition of visible elements introduces additional identities between elements. Regularities, such as symmetries, iterations, and alternations, depend on the order of the elements. The regularities of the visible structure form the basis for a second constraint on compatible extensions, namely the *compatibility of regularity.* This means that only those interpretations are considered in which the completed shape bears the same kinds of regularity as the visible part does.

In future research the impact of both constraints on the completion process needs to be investigated. In our view such constraints will pave the way toward a concept of a generative process in pattern completion that yields a restricted number of interpretations comprising both global and local completions. This agrees with the presented model in which all interpretations are treated in the same way, so that the distinction between global and local completions appears to be post hoc and therefore irrelevant in the explanation of perceived pattern interpretations.

APPENDIX

Quantifying Complexities

Coding rules and information load

In Structural Information Theory three types of regularity play a crucial role: iteration, symmetry, and alternation. The coding rules that describe these regularities are illustrated in Table A1. The encoding procedure starts with a symbol series and extracts as much regularity as possible from this symbol series. The result is a so-called minimum code. The number of parameters at all hierarchical levels in that minimum code is taken as the information load I of that code, reflecting the amount of irregularity in the series (see Van der Helm, Van Lier, & Leeuwenberg, 1992). For example the encoding of 'abab' results into '2*(ab)'. The information load of this code is 3, because of the symbols 'a' and 'b' (parameters at the lowest level) and the group 'ab' (parameter at the highest level). The encoding procedure, from a symbol series to its minimum code, has been implemented in a computer algorithm called PISA (Van der Helm, 1988).

Regularity	Symbol Series	Code	Information Load
Iteration	aa	2*(a)	1
Symmetry	abcba	S[(a)(b),(c)]	3
Alternation	abac	<(a)>/<(b)(c)>	3

Table A1. The three types of regularity used in the Structural Information Theory. Encoding of a symbol series proceeds by extracting these regularities from the series. The information load of the code reflects the amount of irregularity in the series.

Determination of I for a shape

In Figure A1, pattern 2.2 and its global and local completions are given once more. The determination of the complexity of a shape starts with labeling all lines and angles such that all equal lines or angles are labeled with the same symbol. Next, the contour of each shape is represented by a symbol series in which the order of the contour elements is preserved. The encoding of the global shape results in the minimum code '3*(S[(k),(b)]a)', which has an information load of 4 (parameters 'k', 'b', 'a', and '(S[(k),(b)]a)'. Therefore I(A)=4. The encoding of the local shape results in the minimum code 'S[(l)(b)(k),(a)]c' which has an information load of 5 (parameters 'l', 'b', 'k', 'a', and 'c'). Therefore I(B)=5.

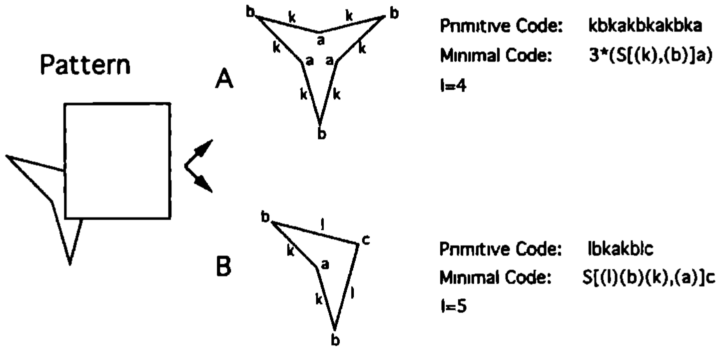


Figure A1. The encoding procedure as performed for a two-dimensional shape. First, the contour of a shape is represented by a symbol series, such that equal lines or angles are represented by the same symbol and such that their order and identity are preserved. Second, the complexity of the shape is determined by the information load (I) of the minimum code of that symbol series.

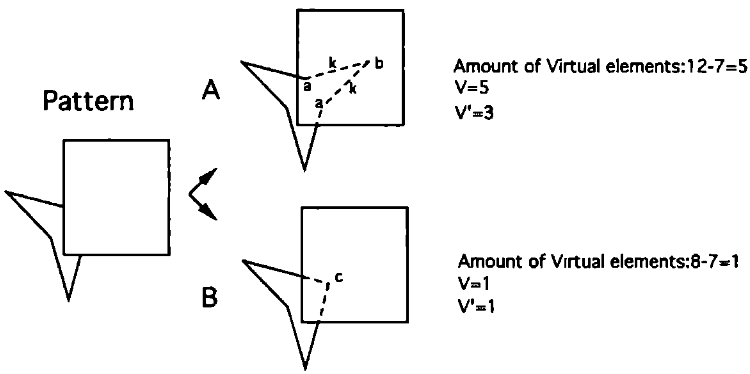


Figure A2. The complexity (V) of the amodal part of a shape is given by the difference between the total number of contour elements of the shape and the total number of completely or partly visible contour elements of that shape. The complexity (V') is obtained by encoding the series of virtual elements.

Determination of V and V'

In Figure A2, pattern 2.2 and its global and local completions are given once more. V is defined by the number of virtual elements. This number is given by the difference between the total number of contour elements of a shape and the total number of completely or partly visible contour elements of that shape. Consequently, the continuation of a visible edge behind an occluding surface does not increase the complexity of the amodal part. The global completion (A) of the pattern in Figure A2 requires five virtual elements, labeled 'a', 'k', 'b', 'k', 'a'. Therefore, V(A)=5. The local completion (B) requires one virtual element, labeled 'c'. Therefore, V(B)=1.

The determination of V' proceeds by encoding the series of virtual elements. For the global completion the encoding of the series 'akbka' results in the minimum code 'S[(a)(k),(b)]', which has an information load of 3 (parameters 'a', 'k', and 'b'). Therefore, V'(A)=3. For the local completion the encoding obviously results in the symbol 'c'. Therefore, V'(B)=1.

"Diversity by Simplicity"

Chapter 4

Multiple completions primed by occlusion patterns

Abstract
There is a strong tendency to complete a partly occluded shape. Two types of pattern completion, global and local, are frequently reported. By means of the primed-matching paradigm, it has previously been shown that global completions are prevalent for stimuli in which regularity is abundantly present. In our study the primed-matching paradigm is applied to such stimuli in order to find out whether the rival local completion is generated as well. Therefore anomalous completions are added to the experimental design. Priming effects both on global and on local completions are compared with priming effects on those anomalous completions. The data indeed suggest that the occlusion patterns evoked not only a global but also a local completion.

1 Introduction

Usually objects occlude parts of themselves and parts of other objects. Yet we do not experience a fragmented world. Apparently the visual system completes partly occluded objects, rapidly and unconsciously. This completion phenomenon has been studied a number of times during past years. Without claiming completeness let us mention a few of these studies: Boselie, 1988; Boselie, 1994; Boselie & Wouterlood, 1989; Buffart, Leeuwenberg, & Restle, 1981, 1983; Dinnerstein & Wertheimer, 1957; Gerbino and Salmaso, 1987; Kanizsa & Gerbino 1982; Kellman & Shipley, 1991; Sekuler & Palmer 1992; Sekuler, Palmer & Flynn 1994; Sekuler 1994; Takeishi, Murakami, Nakazawa & Shimojo, 1993; Van Lier, Van der Helm, & Leeuwenberg, 1994, 1995; Wouterlood & Boselie 1992. Although these studies were focused on various aspects of pattern completion, they all dealt with the perceived form of the occluded shape. The topic is illustrated in Figure 1. Three interpretations of the left pattern are shown on the right. Figure 1A represents the 'mosaic' interpretation in which an L-shaped form is juxtaposed to a square, whereas Figure 1B represents an occlusion interpretation, in which the background figure is completed into a rectangle. Obviously many more completions are possible but unlikely, such as the anomalous completion in Figure 1C. In this paper we will focus only on patterns that evoke occlusion interpretations.

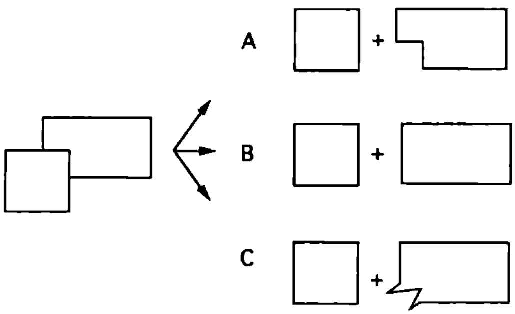


Figure 1. Three interpretations of the pattern on the left-hand side are given. A represents a 'mosaic' interpretation, B the preferred completion, and C an anomalous completion.

1.1 *Global and local completions*

Two types of pattern completion often appear to be relevant: completions based on global simplicity and completions based on local simplicity (see Figure 2). The completion A in Figure 2 is based on global simplicity. That is, the completed background shape reveals a maximum of regularities, which is reflected by, for example, its number of axes of symmetry. The completion B in Figure 2 is based on local simplicity. This local simplicity corresponds with the 'good continuation' of the visible contours of the background shape until they meet.

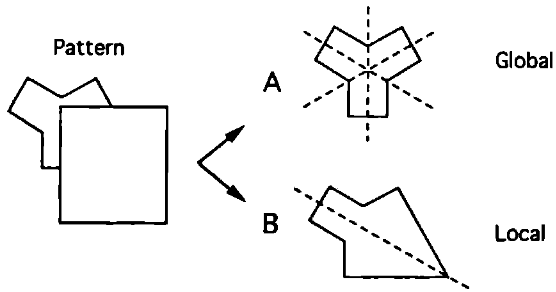


Figure 2. Two completions of the pattern on the left-hand side are given. A represents the global completion and B the local completion. The global completion is based on a tendency towards a maximum of regularity of the completed shape, while the local completion is based on 'good continuation' of the contours of the background shape. In the present case the global shape has three axes of symmetry and the local completion one axis of symmetry.

During past decades, arguments for the prevalence of either global or local completions in visual occlusion have been put forward, often related to certain pattern properties. In general, 'local' theories rely strongly on the impact of local cues, such as specific discontinuities of contours at points of occlusion. The Gestalt principle of good continuation is an important aspect in these theories. For example, in the completion model advocated by Wouterlood and Boselie (1992), a completion based on good continuation of the occluded contours is predicted whenever specific junction types or combinations of those junctions occur. Although Boselie (1994) demonstrated that local aspects also have a strong influence in regular patterns, their model so far is restricted to irregular patterns. The local-completion theory of Kellman and Shipley (1991) may be regarded as a formalization of the good-continuation principle. They argued that completion is reached by a smooth continuation of contours at points of occlusion. Consequently, their model disregards the influence of pattern regularities in predicting perceived completions. In contrast, 'global' theories take into account the regularities of the whole pattern in predicting completions. The Gestalt principle of Prägnanz plays an important role in these theories. Buffart, Leeuwenberg, and Restle (1981, 1983) combined a coding scheme with the global-minimum principle, stating that the simplest completion will be perceived. Despite the initial success of their approach, various patterns have been constructed for which the perceived shape is not the simplest (e.g. Rock, 1983; Kanizsa, 1985; Boselie, 1988).

The ongoing controversy between global and local theories led some researchers to the conclusion that both global and local aspects play a role in pattern completion. Boselie (1988) argued that in a case where two locally simplest interpretations can be made, the globally simplest will be preferred. Recently, Sekuler (1994) gave a qualitative description of a completion model in which the saliency of global and local completions depends on the number and orientation of the axes of symmetry. We demonstrated (Van Lier, Van der Helm, Leeuwenberg, 1995) a relation between the degree of occlusion and the saliency of a global completion. Moreover, we presented (Van Lier et al. 1994) a completion model in which regularities within and between shapes as well as the degree of occlusion are quantified. The model predicts completions in which the sum of these quantified aspects is minimal. Other integrative approaches such as that of Shimaya (1994) also indicate that both global and local aspects are crucial with respect to the perceived interpretation.

1.2 *Single versus multiple completions*

In this paper, however, we do not go into detail on the question of which specific pattern properties support global or local completions, nor do we elaborate on differences between existing theories with respect to the specific definitions of global and local completions. As indicated already, we simply will consider completions to be global if the completed shape reveals a maximum of symmetry, and local if it is reached by linear good continuation of the occluded contours. Given the different types of completions, we will deal here with an aspect of the completion process by questioning whether the perceptual system processes either global or local completions, or both global and local completions. Herbart (1850) has already suggested that the degree to which one interpretation is preferred to another is the result of competition between several possible candidates. In line with this tradition, Mens and Leeuwenberg (1988) demonstrated the hidden presence of alternative interpretations for certain visual patterns. Furthermore, it was argued by Buffart et al. (1983) that, in the case of visual completion, the relative dominance of completions depends on their relative complexity. Also, in Sekuler's (1994) qualitative model on pattern completion the generation of multiple completions is suggested as it concerns both a global and a local completion-processing module. In Van Lier et al. (1995) we discussed the plausibility of competition between global and local completions, using the results of a spontaneous pattern-interpretation task, in which subjects had to draw the preferred completion, and the results of a simultaneous-matching task, partly adopted from Gerbino and Salmaso (1987). The competitive aspect between completions gained support from the finding that the strength of a specific global completion depends on the strength of the local completion. This interdependence already suggested the processing of both global and local completions. Here we aim to converge evidence for the generation of multiple completions by means of a more straightforward test: the primed-matching paradigm.

2 Priming pattern completions

Recently, the primed-matching paradigm was introduced in the research field of pattern completion by Sekuler and Palmer (1992). This paradigm turned out to be a useful tool to assess a subject's perceptual representation. The essence of the primed-matching paradigm lies in a comparison between the effects of different primes on an immediately following matching task. In that task, subjects had to judge as fast as possible whether two simultaneously displayed shapes are equal or not. The inferences drawn from results obtained by the primed-matching paradigm are based on previous findings that the response time to *identical* items is a function of the representational similarity between the items and the prime (cf. Beller, 1971; Rosch, 1975a, 1975b; Sekuler & Palmer, 1992). High similarities appeared to facilitate the response. Figure 3 shows the kind of patterns of the study of Sekuler and Palmer (1992).

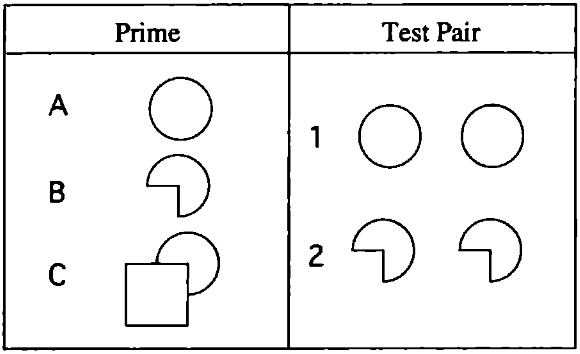


Figure 3. Primes and test pairs as can be used in the primed-matching paradigm. After prime durations of about 200 ms, primes A and C have the same facilitating effects on test pair 1, whereas primes B and C have different facilitating effects on test pair 2.

In an experimental trial, one of the primes on the left can be succeeded by one of the test pairs on the right. According to Sekuler and Palmer's findings a 'same' response on test pair 1 (two circles) requires less response time after prime A (the circle) than after prime B (the 'pacman'). Correspondingly, the 'same' response on test pair 2 (two pacmen) will be faster after prime B than after prime A. The crucial prime now is the ambiguous prime C, which can be interpreted either as a complete circle behind a square, or as a pacman juxtaposed to a square. It appeared that after a prime duration of a few hundred milliseconds, prime C and prime A had the same facilitating effects on test pair 1. Moreover, prime C did not facilitate responses on test pair 2. These results provided strong indication that prime C was interpreted as a case of visual occlusion in which the background shape was completed into a full circle. The variation of prime duration enabled Sekuler and Palmer to follow the time course of the completion process. Their results suggest that the completion process is finished after about 200 milliseconds.

The occlusion patterns in the study by Sekuler and Palmer (1992) were such that the global completion had the same shape as the local completion. Recently, Sekuler, Palmer, and Flynn (1994) used the primed-matching paradigm in order to investigate patterns whose global completions were different from the local completions. In that study, occlusion patterns were used for which the global completion yielded more than one axis of symmetry. For priming durations of 150 ms up to 1000 ms, the effects of primes with occluded shapes (the occlusion prime) were compared with those of primes having either an unoccluded globally completed shape or an unoccluded locally completed shape. It appeared that the effects of the occlusion prime were more similar to the effects of primes with the unoccluded globally completed shape. Sekuler et al. (1994) concluded that completions of occlusion patterns were not dominated by a local process, at least not for their set of patterns. That is, at early stages of the completion process, the occluded shapes are completed in such a way that the complete shapes possess a maximum of symmetry. In another recent study Sekuler (1994) additionally showed that completion depends on the number and orientation of the axes of symmetry. Sekuler concluded that, in contrast with the results on the highly regular patterns, local completion processes may dominate in case of limited pattern regularities.

In the above studies, priming effects of occlusion patterns were compared with priming effects of patterns in which either the global or the local completion was completely visible. In that way it could be investigated whether the global or the local completion was dominant. We pose another question here: does the dominance of one type of completion imply the absence of the other type of completion or might the latter completion be generated as well? In view of the primed-matching paradigm we question whether these nondominant completions are not primed at all or whether they are primed weakly. Indeed, if the latter is the case it supports the notion that both global and local completions are generated by the perceptual system. Our goal here is to investigate this perceptual relevance of global and local completions for a specific occlusion pattern. Microgenetic processing aspects dealing with questions such as whether these completions are generated in parallel or sequentially or whether completions are concurrently or alternately present are different issues and lie beyond the scope of this study.

In the following experiment we use patterns in which regularity is abundantly present. Anomalous completions of the occlusion prime are added to the experimental design. As a result, local completions will not only contrast with global completions, but also with those anomalous completions. The latter comparison will be crucial with respect to the question of whether the local completions are generated as well.

3 Experiment 1

3.1 *Subjects*

Thirty students of the University of Nijmegen participated in the experiment. All participants received course credits.

3.2 *Stimuli*

We restricted ourselves to a small set of patterns in which global completions are prevalent. All patterns stem from our previous research (Van Lier et al. 1995) (see Figure 4). Notice that the globally completed shapes either have at least three axes of symmetry or are at least threefold rotation symmetric. For each pattern three completions are considered: a global completion, a local completion, and an anomalous completion. Each pattern gives rise to 5 different primes and 6 different test pairs. An example is given in Figure 5. In this figure all primes and test pairs for the first pattern

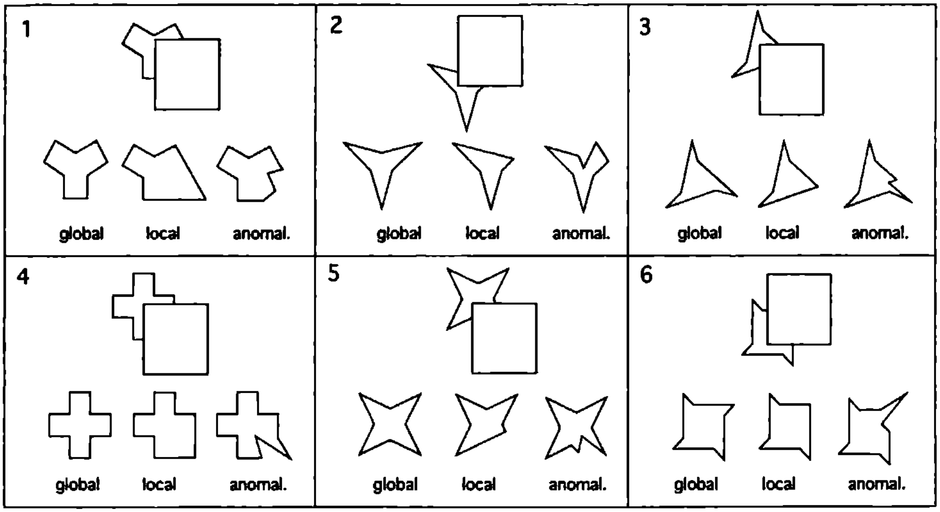


Figure 4. All occlusion patterns that served as an occlusion prime in Experiment 1 are depicted. Beneath each pattern three completions are given: global, local, and anomalous, respectively.

of Figure 4 are shown. Prime A is the occlusion prime, B the global foreground prime, C the local foreground prime, D the anomalous foreground prime, and E represents the no-prime condition. The six test pairs consist of the following combinations of shapes: global/global, local/local, anomalous/anomalous, global/local, anomalous/global, local/ anomalous. Each combination of prime and test pair represents a stimulus presentation. Thus, each occlusion pattern of Figure 4 induces 5*6=30 stimuli, which will be referred to as a 'stimulus subset'. Because there are 6 stimulus subsets, there are 6*30=180 stimuli.

Like Sekuler and Palmer (1992), Sekuler, Palmer and Flynn (1994), and Sekuler (1994), we will only consider response times on the test pairs with identical shapes in the analysis, because priming effects may be expected only on pairs with identical shapes (cf. Beller, 1971). In the following, test pair 1, 2, and 3 of Figure 5 will be referred to as the global, the local, and the anomalous test pair, respectively. A foreground prime succeeded by a test pair with shapes that are both identical to the shape of the prime will be referred to as a congruent foreground prime. For example, if prime B in Figure 5 (the global foreground prime) is followed by the global test pair it will be referred to as a congruent foreground prime. The same holds for the combinations (prime C and test pair 2), and (prime D and test pair 3). A foreground prime which is followed by a test pair with identical shapes, but different from the prime, will be referred to as an incongruent foreground prime. For example, if prime B in Figure 5 is followed by test pair 2 or 3, it will be referred to as an incongruent foreground prime. The same holds for the combinations (prime C and test pair 1), (prime C and test pair 3), (prime D and test pair 1), and (prime D and test pair 2).

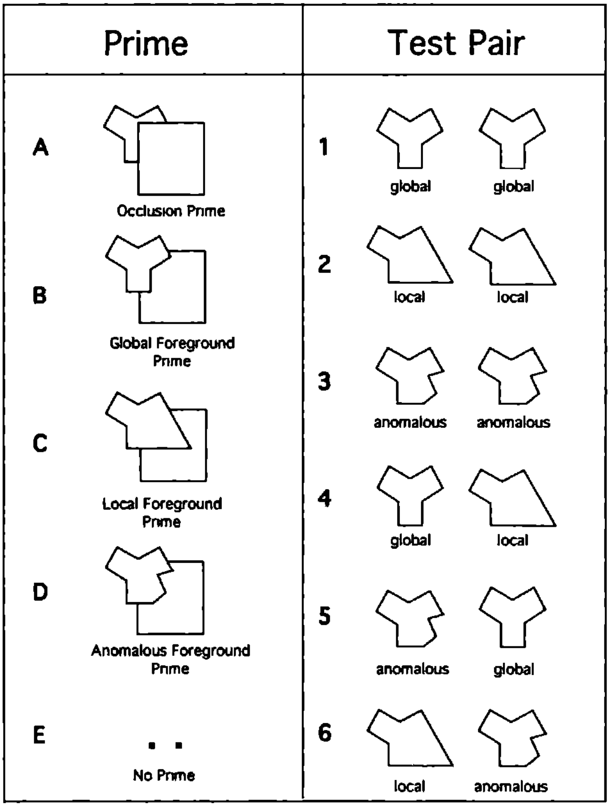


Figure 5. In the design of Experiment 1 each occlusion pattern of Figure 4 gives rise to five different primes and six different test pairs. Each combination of prime and test pair represents a stimulus in the experiment.

3.3 *Procedure*

The stimuli were generated on a computer monitor with a viewing distance of 1 m. The priming pattern was visible within a visual angle of 3 deg. The test pair was visible within a visual angle of 8 deg. In Figure 6 the sequence of events and spatial layout in one trial is shown.

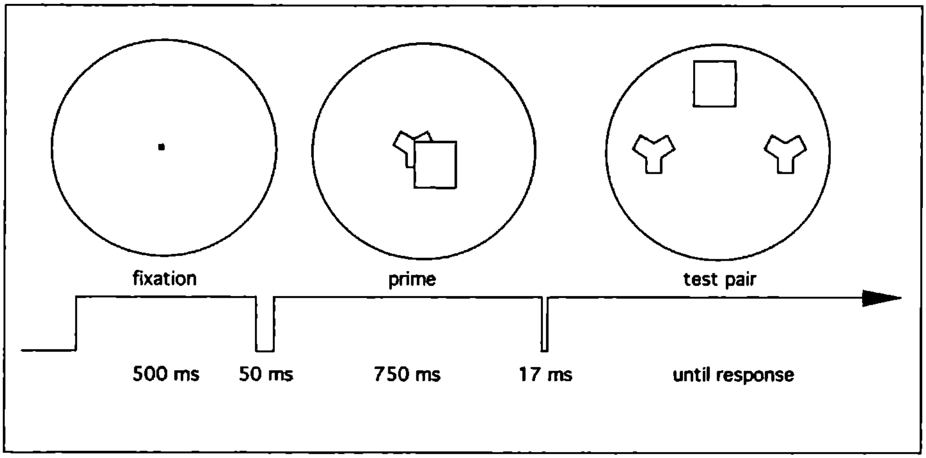


Figure 6. The spatial and temporal layout of the experimental procedure.

First a fixation point was shown at the centre of the screen for 500 ms. After this period the screen was empty for 50 ms. Subsequently the prime appeared. Prime duration was 750 ms, in accordance with Experiment 1 of Sekuler and Palmer (1992). According to the results of Sekuler and Palmer (1992), and Sekuler, Palmer, and Flynn (1994) the completion process is finished within that period. Seventeen ms after the prime disappeared the test pair was shown. One of the two shapes of the test pair was positioned to the left and the other to the right of the previously shown prime. In addition a rectangle appeared in the centre top of the screen in order to avoid a severe weakening of the priming effect due to an apparent motion from the rectangle accompanying the relevant prime shape to one of the shapes in the test pair (see also Sekuler & Palmer, 1992). The test pair remained on the screen until a response was given. Subjects responded by pushing one of two buttons (yes/no) in order to answer whether or not both test shapes were equal. Responses were measured to the nearest millisecond. As in the experiments of Sekuler and Palmer (1992), subjects received visual feedback on their response time. If an answer was incorrect this was reported to the subject. Incorrectly answered stimuli were presented once more at a later stage in the experiment. The order of presentation was randomized for each subject.

3.4 *Results*

Remember that only response times stemming from correct 'yes' responses are considered. The mean response times for each prime x test pair combination are plotted in Figure 7. In this figure the test pairs are plotted on the horizontal axis. The various primes are represented by different symbols. For each test pair, homogeneous subsets according to Tukey's HSD procedure ($p<0.05$) are indicated by ovals.

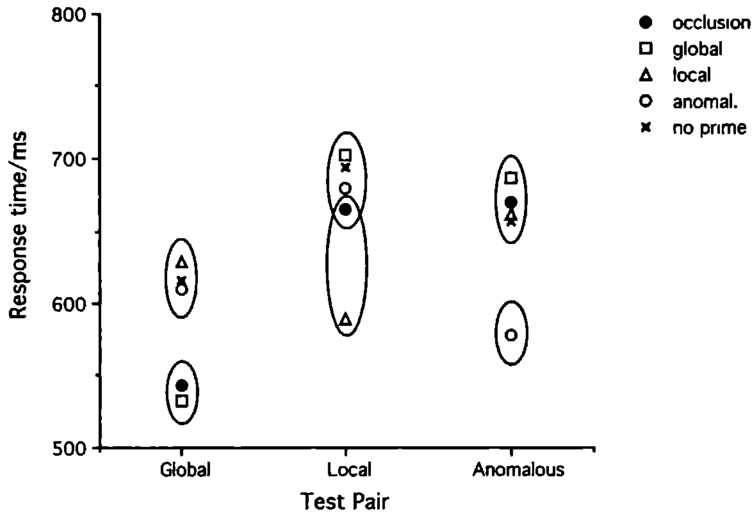


Figure 7. The mean response times on all prime x test pair combinations in Experiment 1 On the horizontal axis the test pairs are given The primes are represented by different symbols. For each test pair, homogeneous subsets according to Tukey's HSD procedure ($p<0.05$) are indicated by ovals.

In Figure 7, it can be seen that congruent foreground primes, for example the global foreground prime followed by the global test pair, evoke the fastest response times. This is exactly what is expected on the basis of the assumptions underlying the primed-matching paradigm. Accordingly, the incongruent foreground primes evoke relatively slow response times. For example, the response time on the global test shapes is the slowest after the local foreground prime, whereas the response time on the local test shapes is the slowest after the global foreground prime. The issue here is the priming effect of the occlusion prime on the test pairs. The results of Tukey's HSD test on the response times already indicate the varying effects of the occlusion pattern on the three test pairs. In the following we evaluate the priming effects of the occlusion prime. This priming effect is supposed to reveal the strength of the completion of the occlusion prime.

3.5 *Analyses*

Sekuler (1994) and Sekuler, Palmer, and Flynn (1994) defined the priming effect for a given prime by means of the difference in response time on global and local test pairs after the prime, minus this difference after no prime. The response times after no prime served as a 'baseline', as the inclusion of these response times accounted for the possibility that subjects responded faster to global test pairs then to local test pairs, even after no prime. In this way it could be tested whether the priming effects of the occlusion prime were more similar to those of the global foreground prime or to those of the local foreground prime. Our design differs from that of Sekuler (1994) and Sekuler et al. (1994) in that anomalous completions are also included. We therefore reconsider the priming effect. In the present analyses we will compare the priming effects of the occlusion prime on the global, local, and anomalous test pairs. Below we give two analyses, thereby defining the priming effect in two different ways.

3.5.1 Analysis 1

For each test pair, the response times after no prime, the occlusion prime, and the congruent foreground prime will be considered. If the occlusion prime is completed in such a way that it is the same as the test shapes, then we expect the response time after the occlusion prime to be shorter than the response time after no prime. Also, we expect that the response time after the occlusion prime will approach the response time after the congruent foreground prime. As both the response time after no prime and the response time after the congruent foreground prime may be regarded as a baseline value we will take them both into account, by taking the mean of these response times. The priming effect of the occlusion prime on a given test pair will be determined by the difference between this mean baseline value for a given test pair and the response time after the occlusion prime on that test pair:

$$PE(OP|TP) = \overline{RT\{(NP|TP),(CFP|TP)\}} - RT(OP|TP)\,, \tag{1}$$

where PE is the Priming Effect, OP Occlusion Prime, TP Test Pair, RT Response Time, NP No Prime, and CFP Congruent Foreground Prime.

In Figure 8, the mean PE values for Experiment 1 are shown. An ANOVA for repeated measurements with PE as the dependent variable has been performed. The main effect of test pair was significant ($F(2,58)=11.24$; $p<0.001$). There was no significant interaction between test pair and the six stimulus subsets ($F(10,290)=1.32$). In addition, one tailed T-tests were performed on the mean priming effects; the results are the following: PE(OP|Global) > PE(OP|Local), $t=2.57$ ($p<0.01$); PE(OP|Global) > PE(OP|Anomal.), $t=4.87$ ($p<0.001$); PE(OP|Local) > PE(OP|Anomal.), $t=1.97$ ($p<0.05$).

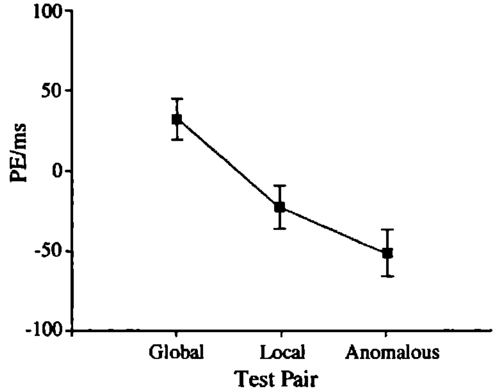


Figure 8. Experiment 1. The mean priming effect (PE) according to analysis 1.

Discussion

The priming effect of the occlusion prime on the local shapes lies between the priming effects on the global and anomalous shapes. The fact that the priming effects of the occlusion prime on both the global and the local test shapes are significantly higher than the priming effect on the anomalous test shapes supports the notion that besides the global completion, the local completion is generated.

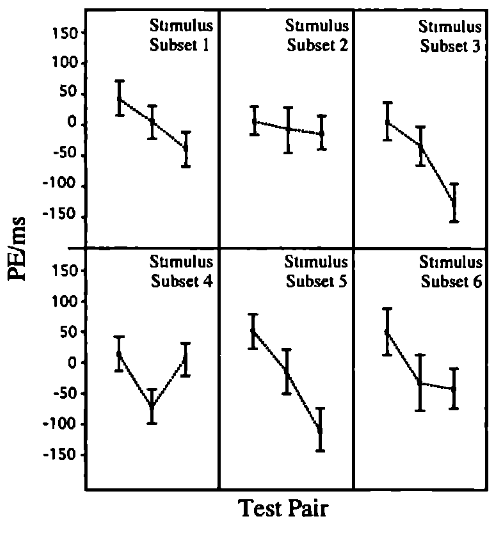


Figure 9. Experiment 1. The priming effect (PE) according to analysis 1 is plotted for each stimulus subset. The sequence of test pairs from left to right is: global, local, anomalous.

In spite of the clear results on the mean data it is expedient to take a closer look at the tendencies within each stimulus subset. In Figure 9 the priming effect within each stimulus subset is depicted. In five out of the six cases, the priming effect follows the tendency of the mean data, although differences between the priming effects on local and anomalous test shapes are fairly small in stimulus subsets 2 and 6. The priming effect within stimulus subset 4 reveals a clear exception with respect to the mean data. Within this stimulus subset, the priming effect on the anomalous shapes appears to be almost the same as the priming effect on the global shapes. Does this mean that the occlusion prime is perceptually completed in an anomalous way, exactly as the one in Figure 4? This seems to be highly unlikely. Apparently we have to preserve some caution with respect to the defined priming effect.

It can be questioned whether the priming effect of the occlusion prime, as defined in the present analysis, is solely caused by the perceptual completion of the occluded shape in the occlusion prime. Priming effects also could stem from the similarity between the visible part of the occlusion prime and the test shape. So, because of that part, even incongruent foreground primes might facilitate responses on a specific test pair. If the shorter response times after the occlusion prime are due to completion, they have to be different from the response times after the incongruent foreground primes. In the following analysis the priming due to this similarity is accounted for.

3.5.2 Analysis 2

Just like the occlusion prime, the incongruent foreground primes have the visible part of the occluded shape in the occlusion prime in common with the test shape. Therefore, in the present analysis we will consider the response times on the set of primes (S), consisting of the incongruent foreground primes and the occlusion prime as a baseline value. In addition, the priming effect of the occlusion prime will be conceived as the *distinctiveness* of the occlusion prime with respect to (S). This priming effect (PE') will be defined by the following expression:

$$PE'(OP|TP) = \frac{\overline{RT(S|TP)} - RT(OP|TP)}{\sigma_{\{RT(S|TP)\}}} \quad . \tag{2}$$

The numerator, being the difference between the mean response time of S and the response time after the occlusion prime, expresses the relative facilitation caused by the occlusion prime. This relative facilitation is normalized by the variation (σ) between the response times: the greater the difference between the response times evoked by the incongruent foreground primes and the occlusion prime, the less distinctive the response time of the occlusion prime, and therefore the lower the priming effect.

If we consider all data, the PE' values of the occlusion prime on the different test pairs are: PE'(OP|Global)=0.4188; PE'(OP|Local)=0.1598; PE'(OP|Anomal.)=-0.0146. The mean PE' values are plotted in Figure 10. An ANOVA for repeated measurements with PE' as the dependent variable was performed. The main effect of test pair was significant ($F(2,58)=14.56$; $p<0.001$). There was no significant interaction between test pair and the six stimulus subsets ($F(10,290)=0.89$). T-tests performed on the mean priming effects reveal the following results: PE'(OP|Global) > PE'(OP|Local), $t=3.14$ ($p<0.01$); PE'(OP|Global) > PE'(OP|Anomal.), $t=5.07$ ($p<0.001$); PE'(OP|Local) > PE'(OP|Anomal.), $t=2.39$ ($p<0.05$).

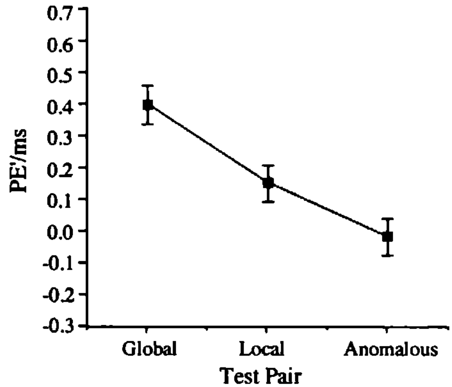


Figure 10. Experiment 1. The mean priming effect (PE') according to analysis 2.

Discussion

The overall tendency does not differ from that of analysis 1. The priming effect PE' is the highest for the global shapes, the lowest for the anomalous shapes, whereas PE' on the local completion lies in between. In Figure 11, PE' within each stimulus subset is depicted. Comparing the graphs of Figures 9 and 11, the different results on stimulus subset 4 are most noticeable. Note that in case of stimulus subset 4 the number of lines and angles in the visible part of the occluded shape is higher than for any other stimulus subset. In addition the anomalous shape contains very distinctive oblique lines which enhance its salience. The combination of both aspects probably causes the facilitation of the responses on the anomalous shapes, not only after the occlusion prime, but also after the incongruent foreground primes. The present analysis accounts for this. A disadvantage of this analysis, however, is that it does not explicitly test in what way the occlusion prime is completed. Note further that the priming effects according to the present analysis not only depend on just the visible part of the occluded shape (which is the part that the occlusion prime and the incongruent foreground primes have in common), but, more generally, on the perceptual similarity between the incongruent foreground primes and the occlusion prime. The present analysis, therefore, rather accounts for an estimated contribution of the visible part. Nevertheless, the fact that the second analysis leads to the same global ordering of the priming effects of the occlusion prime as analysis 1, being the highest on the global shapes, the lowest on the anomalous shapes, and intermediate on the local shapes, comprises additional support for this ordering. The clearly different results on stimulus subset 4, however, demonstrate that some caution is necessary when interpreting the analyses.

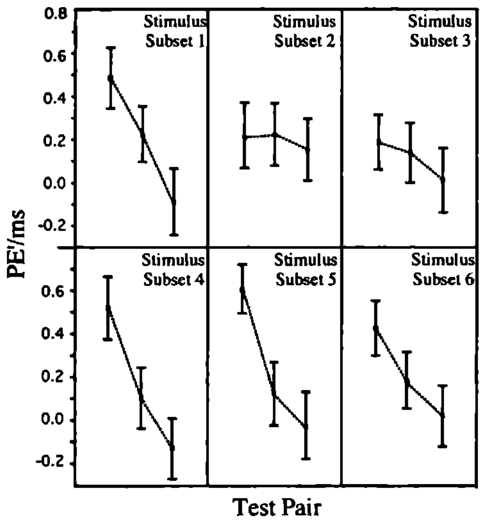


Figure 11. Experiment 1. The priming effect (PE') according to analysis 2 is shown for each stimulus subset. The sequence of test pairs from left to right is: global, local, anomalous

Within the scope of the present discussion we regard the two analyses as supplementary with respect to each other, without preferring one analysis to the other. Our main point here is that the different priming effects on the global or local shapes on the one hand and the anomalous shapes on the other hand, for both analyses, support the notion that for a given occlusion pattern, both global and local completions are generated by the perceptual system. However, there still is a reservation to be made, which will now be dealt with.

4 Experiment 2

It is possible that, for example, only the global completion is generated. In that case, the priming effect on the local completion might be due to a *spreading* of the priming effect to completions that are more or less similar to the global completion. This spreading effect may affect the local test pair more than the anomalous test pair.

In order to control for the occurrence of such a spreading effect, a second experiment was set up in which many more anomalous completions were added. These completions ranged by means of small changes from a global completion to a local completion. The rationale behind this experiment setup is that if the priming on the local completion in fact stems from the global completion, the spreading should also affect intermediate completions.

4.1 *Subjects*
Thirty students of the University of Nijmegen, who did not take part in Experiment 1, participated in the experiment. All participants received a small payment.

4.2 *Stimuli and procedure*
The first occlusion pattern of Figure 4 was used in the experiment. In the experiment setup, seven different completions were considered. These completions ranged by small changes from global to local; see Figure 12. In total there were nine different primes:

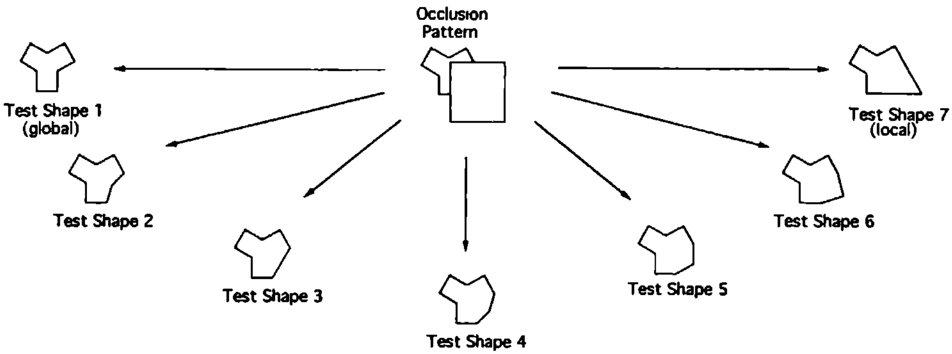


Figure 12. The occlusion prime and test shapes of Experiment 2. The test shapes range by means of small changes from a global completion to a local completion.

the occlusion prime, seven foreground primes, and the no prime (again represented by two dots). The foreground primes consisted of one of the seven shapes of Figure 12 in front of a rectangle. In each trial, one of these primes was followed by one of fourteen test pairs. Seven test pairs consisted of identical shapes, involving the seven completions. The seven other test pairs consisted of nonidentical test shapes, being arbitrary combinations of these completions, but such that if one considers the whole experiment, all test shapes had the same frequency of occurrence. The experimental procedure was the same as in the previous experiment.

4.3 *Results*

In Figure 13A, the mean response times and standard errors are shown. As in the previous analysis, only test pairs with identical test shapes are considered. The response times on the incongruent foreground primes for each shape comprise the mean of three subsequent incongruent foreground primes, closest to the test shapes. Only these primes were considered in order to account for the fact that the incongruent foreground primes of the middle test shapes of Figure 12 deviate less from the test shape itself, as they are situated around this test shape, than the incongruent foreground primes of the outer test shapes of Figure 12.

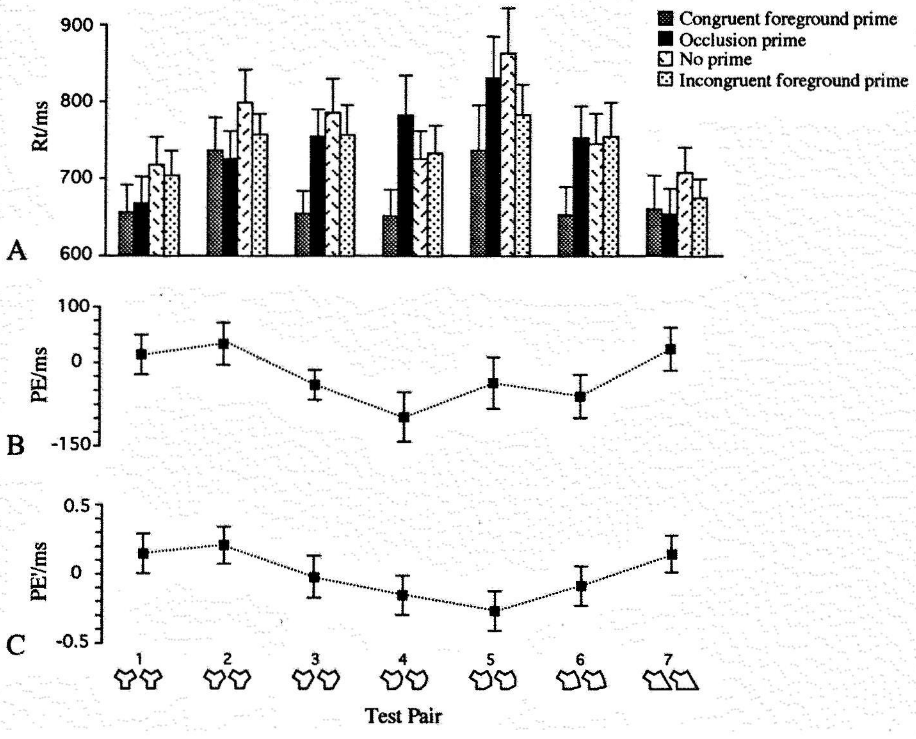


Figure 13. The results of Experiment 2. (A) The mean response times (RT) after the various prime types; (B) the priming effects according to definition 1 (PE); (C) the priming effects according to definition 2 (PE').

4.4 *Analyses*

In Figure 13B the mean values of the priming effect PE(OP|TP) according to analysis 1 are shown. These values are relatively high 'near' the global completion, decrease to a minimum at test pair 4, and gradually increase to another local maximum at the local completion. The priming effects of the occlusion prime on both the global completion and the local completion are significantly higher than the priming effect on shape 4. ($t=1.88$, ($p<0.05$); and $t=1.99$, ($p<0.05$), respectively). Also, the priming effect on shape 2 (the completion nearest to the global completion) is significantly higher than the priming effect on shape 4 ($t=2.19$, $p<0.05$). The priming effect PE'(OP|TP) according to analysis 2 is depicted in Figure 13C. According to this definition, the lowest priming effect is achieved for test pair 5. Now, the priming effects of the occlusion prime on the global completion and the local completion are significantly higher than the priming effect on shape 5 ($t=1.70$, ($p<0.05$); and $t=2.36$; ($p<0.05$), respectively). Also, the priming effect on shape 2 appears to be significantly higher than the priming effect on shape 5 ($t=2.28$, $p<0.05$).

4.5 *Discussion*

The course of the amounts of priming, with a minimum between the global and local completion, opposes the idea that the priming effect on the local completion is simply due to a spreading of the priming effect caused by the presence of the global completion. The priming effects therefore once more indicate the special status of global and local completions. The relatively high values of the priming effects PE and PE' on shapes 'near' the global and the local completion (especially shape 2) suggest a spreading of the priming effects from the global and local completions to those nearly global and nearly local completions. Note, however, that the data do not definitely exclude the possibility that those completions are generated as well.

5 Conclusion

On the whole, the data support the notion that multiple completions are generated by the visual system. That is, within the present prime duration time of 750 milliseconds one occlusion pattern might evoke global and local, and perhaps even other completions. We conclude that, whatever an explanatory model of pattern completion might look like, its output must be characterized by multiplicity rather than singularity.

PART 3

OBJECTS

"Components by Simplicity"

Chapter 5

From geons to structure. A note on object representation

Abstract
Two models of object perception are compared: Recognition By Components (RBC), proposed by Biederman (1987) and Structural Information Theory (SIT), initially proposed by Leeuwenberg (1969). According to RBC a complex object is decomposed into predefined elementary objects, called geons. According to SIT, the decomposition is guided by regularities in the object. It is assumed that the simplest of all possible interpretations of any object is perceptually preferred.

The comparison deals with two aspects of the models. One is the representation of simple objects: various definitions of object axes are considered. It is shown that the more these definitions account for object regularity and thus the more they agree with SIT, the better the object representations predict object classification. Another topic concerns assumptions underlying the models: the identification of geons is mediated by cues which are supposed to be invariant under varying viewpoints of objects. It is argued that such cues are not based on this invariance but on the regularity of actual objects. The latter conclusion is in line with SIT. An advantage of RBC, however, is that it deals with the perceptual process from stimulus to interpretation, whereas SIT merely concerns the outcome of the process, not the process itself.

1 Introduction

This paper deals with two models for visual object representation. One model is called 'Recognition By Components' (RBC) and was proposed by Biederman (1987). The other model is called 'Structural Information Theory' (SIT) and was proposed by Leeuwenberg (1969, 1971) and elaborated by various researchers at the University of Nijmegen (e.g. Buffart, Leeuwenberg, & Restle, 1981; Collard & Buffart, 1983; Van Tuyl, 1980, Mens & Leeuwenberg, 1988; Boselie & Leeuwenberg, 1986; Van der Helm & Leeuwenberg, 1986, 1991; Van Lier, Van der Helm, & Leeuwenberg, 1994). In fact we have dealt with these two models in a previous paper (Leeuwenberg & Van der Helm, 1991), but in a way that differs from the present one. In that previous paper the two models were contrasted with each other. In the present paper we focus on the characteristics shared by the two models. In fact, we start from RBC and consider the changes that would transform this approach into SIT. This strategy is used with respect to two aspects of the models. The first aspect to be dealt with is the actual representation of objects as prescribed by the models (section 2). The second topic which is discussed refers to assumptions underlying the two models (section 3).

2 From axis to superstructure

The two models will not be presented fully, but only as far as relevant for comparing the two models. As mentioned above, we start from RBC. Therefore, we first indicate some features of this approach.

2.1 *Recognition by components (RBC)*

Biederman (1987) assumes that complex objects are perceived as compositions of simple objects, in a manner analogous to the way words are recognized on the basis of about 40 phonemes. He distinguishes 36 different simple objects, called 'geons'. Each of them can be identified from their retinal projections. We will not deal with the identification process, but merely with the geon properties with respect to which geons differ from each other. A geon is specified by an axis and a cross section. The cross section is orthogonal to the axis and may vary in three ways. The axis may only vary in one way. Thus, to specify a geon by means of a so-called geon code, four variables have to be specified, as follows.

i) The contour of the cross section consists merely of straight-line segments (S), or includes one or more circular curves (C).

ii) The cross section is symmetrical (+) or asymmetrical (-). In fact Biederman distinguishes three levels for this variable but, for our purpose, this binary categorization suffices.

iii) Going along the axis, the cross section is constant (+) or varies in size. In the latter case, the cross section expands (-), or both expands and contracts (- -).

iv) The axis is a straight line (S) or a circular curve (C).

An instance of a geon is a tube, with (C + + S) as geon code. The first three indices refer to the cross section, being circular (C), symmetrical (+) and constant (+). The fourth index (S) refers to the straight axis of the tube. Another instance of a geon is a banana. Its geon code is (S + - - C). The square-shaped cross section has straight-line segments (S) and is symmetrical (+). The size of this cross section increases and decreases (- -). The axis is curved (C).

In our analysis of RBC, we will make use of such geon codes. Obviously such codes depend on the way axes and cross sections are defined. According to Biederman, the axis primarily is the component with the 'longest extension'. In case there is no unambiguous longest component, the axis is orthogonal to the most constant and symmetrical cross section. The latter case is illustrated by means of Figure 1. This figure stands for a geon. The question is how this geon can be represented in the best way. The height, width and depth of the shape in Figure 1A are about equal. Therefore, three axes, x, y and z can be considered, each with a different cross section. The x-axis, shown in Figure 1B, implies a cross section with varying proportions. It varies in both size and form. Therefore, this axis is a bad choice. The vertical y-axis, in Figure 1C, and the horizontal z-axis, in Figure 1D, both imply constant cross sections, but the cross section in Figure 1C is less symmetrical than the cross section in Figure 1D. Therefore, the z-axis is the best choice.

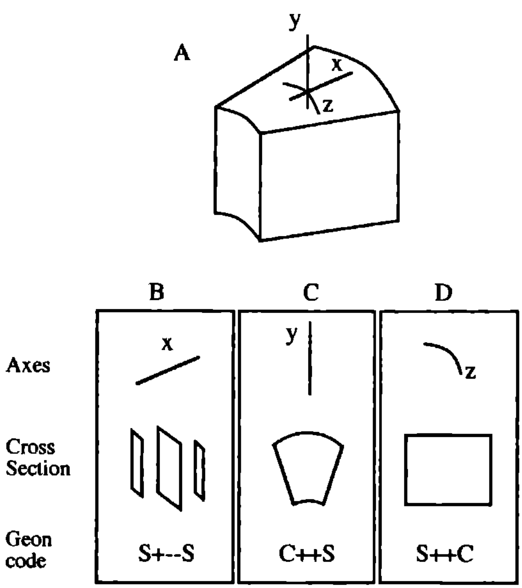


Figure 1. For the geon object in (A), three axes *x*, *y*, and *z* are possible. The cross section of these axes are shown in (B), (C), and (D) respectively.

When a geon object is simple, it is often quite clear which components are to be chosen as the axis and the cross section in its geon code. For many geon objects, however, this is not clear at all. Both metrical and structural criteria are involved in the choice of geon axes. However, the length of an axis is hardly comparable with the constancy and symmetry of a cross section. Length is a quantitative property and is called a 'metrical aspect' (MacKay, 1969). Metrical identical values lead to constancies and symmetries. These regularities are qualitative properties and are called 'structural aspects' (Mackay, 1969). We will demonstrate, for various concepts of axes, that the less that metrical and the more that structural aspects are involved in the definition of axes, the more it is clear what the axis means for various objects, and the better the geon codes predict object classification.

Three different concepts of axes will be considered that are consistent with the RBC rules, i.e. with the earlier given variables of a geon cross section and axis. We will indicate them by axis 1 to axis 3. We will see that, among them, only the third concept is consistent with SIT. In the demonstration of the axis concepts, we make use of the objects shown in Figure 2 and the way these objects, being geons, were classified by 60 students. Most students (53) judged the similarity between A and B in Figure 2 as higher than the similarity between B and C. In this test, the figures were presented in different positions and orientations.

2.1.1 RBC (axis-1)

The specification of an axis roughly agrees with the one given by Biederman (1987): the axis is primarily specified by its length. If there is no unambiguous longest length, the axis is orthogonal to the most constant and symmetrical cross section.

For A in Figure 2, the axis is obvious: a semicircle. The cross section is a constant trapezoid (see cell A1, Figure 2). For B the assessment of the axis is less obvious. A possible geon code is one that is similar to the one in cell A1: a semicircular axis with an extended trapezoid as constant cross section. However, according to the axis-1 specification, this geon code has to be rejected in favour of a geon code with a longer axis, namely the symmetry axis. Then, along this axis, the cross sections vary but are all symmetrical semicircles (cell B1, Figure 2). Similarly, for C in Figure 2, the long symmetry axis has to be chosen. Along this axis, the cross sections vary but have bilateral symmetry in common (see cell C1, Figure 2).

The geon codes with axis-1 do not agree well with the perceptual classification of the three objects. As indicated in Figure 2, the geon codes given in A1 and B1 differ with respect to all four indices, whereas the geon codes in B1 and C1 differ only with respect to one index.

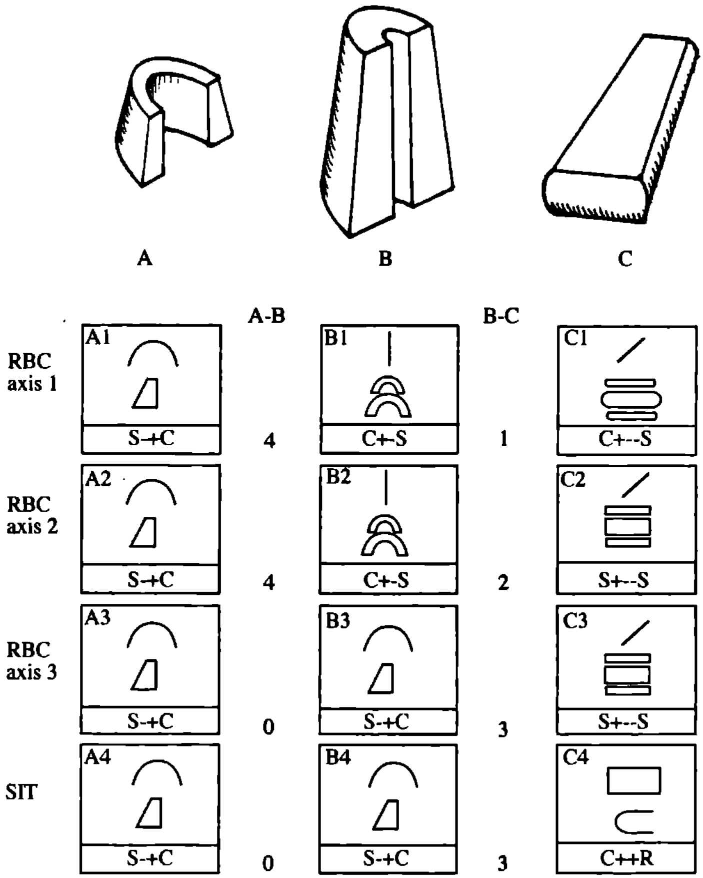


Figure 2. A, B, and C are three geon objects. These objects are represented in four ways. Three of them are compatible with RBC and one only with SIT. In the upper part of each cell, A1,...,C4, a visualized code is presented. The top component of the visualized code refers to the axis or axis structure, the bottom component refers to the cross section. Below the visualized code a symbolic geon code is presented. The numbers between the geon codes refer to the numbers of indices with respect to which these codes differ.

2.1.2 RBC (axis-2)

The axis of an object is again specified by its 'length', but now under the condition that varying cross sections have all angles in common. This condition introduces a structural constraint, but it does not imply that varying cross sections are congruent. The constancy and symmetry of the cross section is again decisive for the axis in case there is no unambiguous longest axis.

This specification does not change the codes for A and B in Figure 2 (see cells A2 and B2), but does change the code for C. According to the axis-1 code of this object, the cross sections are indeed similar but do not have all angles in common. Also Biederman would probably prefer another code for this object, namely the one indicated in cell C2: the axis is vertical, being orthogonal to varying rectangular cross sections.

Notwithstanding the mentioned change, the geon codes with axis-2 do not agree with the perceptual classification of the objects A, B and C in Figure 2. That is, the difference between the codes in the cells A2 and B2 is still larger than the difference between the codes in B2 and C2.

2.1.3 RBC (axis-3)

The definition of axis will now be almost the opposite of the definition given by Biederman but is still consistent with the remaining rules of RBC. Instead of length, constancy is the primary determinant of the axis: the axis is the one for which the cross section is constant. If no constant cross section is at hand, the axis agrees with the longest component, under the condition that the varying cross sections share the angular structure.

This definition changes the code for B in Figure 2 into a code similar to that of A: the axis is semicircular and the cross section a constant trapezoid. The result is that the geon codes for A, B, and C in Figure 2 agree with the perceptual classification of these figures. That is, the difference between the codes of cells A3 and B3 is smaller than the difference between the codes of B3 and C3.

2.2 *Towards SIT*

We have shown that, going from axis-1 to axis-3, the more the definitions of axes account for regularity and constancy, the better geon codes predict the classification of the objects in Figure 2. In fact, so far only axis-3 predicts this classification well. Yet another concept of axis can be considered, which predicts this classification equally well, but is inconsistent with the rules of RBC. This concept leads to another code for C in Figure 2 (see cell C4) from that of axis-3. Before we argue that this new concept accounts for even more regularity than axis-3 and stems from SIT, we will attempt to demonstrate that the code in cell C4 is more plausible than the code in cell C3. This demonstration occurs in two steps, namely by considering the Figures 3 and 4.

According to Biederman (axis-1, axis-2), all four geon objects in Figure 3, except D, can be characterized by a circular axis and a constant trapezoidal cross section. He represents object D by a straight vertical axis and an expanding circular cross section. However, the latter representation is, in our view, implausible as object D just combines the cross section of object B and the axis of object C. According to axis-3 all four objects of Figure 3 should be characterized by a circular axis and a constant trapezoidal cross section.

Object D of Figure 3 is shown again in Figure 4 (object A) together with a few other variants. We have just argued that this object has, according to axis-3, a circular axis. Now, as the difference between this object and C in Figure 4 is equivalent to the difference between a circle and a rectangle, it is reasonable that object C has a rectangular axis. Such an axis is accepted by SIT but not by RBC. As we will argue later on, SIT allows any pattern as axis, whereas RBC only permits straight and circular-line axes. Hence object C in Figure 4 has, according to RBC, a vertical straight-line axis instead of a rectangular axis.

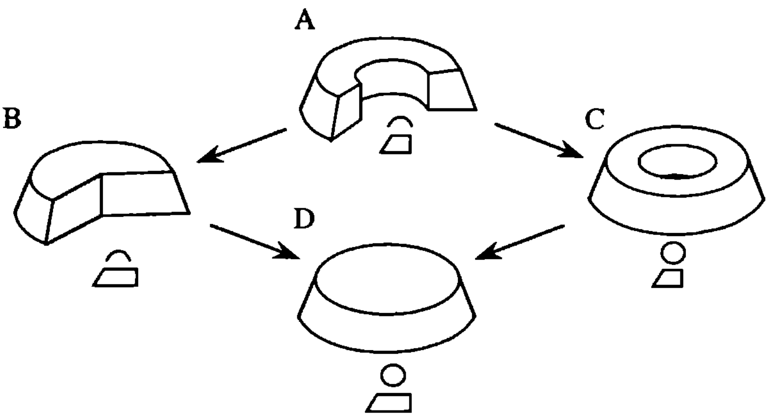


Figure 3. B has a different cross section from A C has a different axis from A Both differences are combined in D Therefore it is reasoned that D has a circular axis and not a straight vertical axis

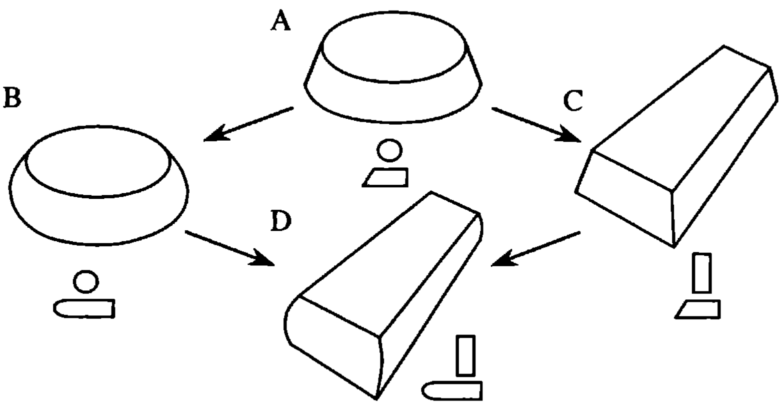


Figure 4. If A has a circular axis, B has a different cross section from A, and C has a different axis structure from A Both differences are combined in D Therefore it is reasoned that D has a rectangular axis structure and not a vertical straight axis

For the reason just given it also reasonable that object D in Figure 4 has a rectangular axis. Its cross section agrees with the cross section B in Figure 4. As C in Figure 2 is equal to D in Figure 4, C in Figure 2 also has a rectangular axis (R). This is shown in cell C4 in Figure 2. The codes for A and B in Figure 2 are the same for RBC (axis-3) and SIT.

2.3 *Structural Information Theory (SIT)*

The most important assumption of SIT is the minimum principle (Hochberg & McAlister, 1953). This principle implies that of all possible representations of a pattern the 'simplest' one is perceptually preferred. The simplest pattern representation maximally accounts for constancies in a pattern. Therefore this representation is related to axis-3 and not to axis-1 or axis-2. A great difference between RBC and SIT is that RBC specifies beforehand the components (geons) of a scene, whereas according to SIT the perceptual components of a stimulus follow from the simplest representation of a stimulus. The kinds of constancies, i.e. regularities, that are taken into account in the representation, are those that satisfy the 'accessibility' criterion, elaborated in Van der Helm and Leeuwenberg (1991).

Another assumption of SIT is that an object representation contains all the information needed to reconstruct the object. We will try to suggest a clarification of this reconstruction for the two objects shown in Figure 5. We start from the axis and cross section components in the visualized codes in A' and B' in Figure 5. These components are supposed to be revealed by the simplest representations of these figures (Leeuwenberg & Van der Helm, 1991).

The cross sections of both codes are represented by the holes in the vertical 'filters' in A'' and B'' in Figure 5. These 'filters' are conceived as moving along the contours of the axes. During this motion the filters should remain orthogonal to the axis surface and orthogonal to the local orientation of the axis contour. The spaces finally selected by the moving filters will then have the shapes A and B shown in Figure 5. The construction of these objects occurs in a manner analogous to the way a carpenter mills these objects from pieces of wood.

In this construction of objects, the axis and cross section play a different role. The axis determines the orientations of the cross sections, but not the other way around: the cross sections do not determine the orientations of the axes. For this reason we replace the term axis by 'superstructure' and the term 'cross section' by 'subordinate structure'. The super- and subordinate structures are hierarchically related components of the simplest representation of a shape and supply the necessary information for the reconstruction of an object from its representation. With respect to the way simplest object representations can be specified, we were more explicit in Leeuwenberg and Van der Helm (1991).

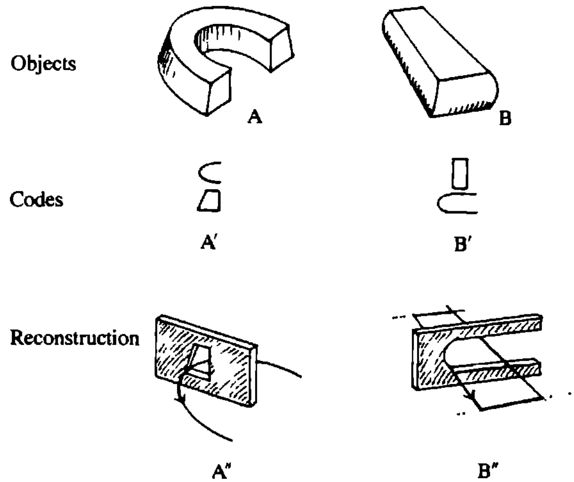


Figure 5. The visualized SIT codes of A and B are indicated by A' and B', respectively. The top components of the codes refer to superstructures. The bottom components refer to subordinate structures A'' and B'' illustrate how the objects can be reconstructed from the visualized codes. The holes in the vertical 'filters' correspond with the subordinate structures. These 'filters' are conceived as moving along the horizontal superstructures. the semicircle for A and the rectangle for B. The spaces, selected by the moving filter holes, agree with the forms of A and B. The dotted lines in B'' indicate that the motion of the 'filter' ought to be slightly prolonged at the angles in order to obtain a solid object.

2.4 *Summary*

By means of demonstrations we have tried to show that if not only structural but also metrical criteria are involved in defining axes, the specification of axes for certain objects is rather unclear and arbitrary. Both kinds of criteria play a role in RBC under the axis-1 and the axis-2 definitions. Another consequence is that such axes are not consistent with the perceptual classification of objects, as shown by the examples of Figure 2. However, if only structural criteria are considered as decisive for the definition of axes, the axes are less arbitrary and lead to better predictions about the perceptual classification of objects. Axis-3 merely uses structural criteria and states that the axis is orthogonal to a constant cross section. However, as RBC only accepts straight-line and circular-line axes, whereas SIT, in principle, accepts any pattern as axis, RBC (axis-3) does not explain well the common and distinctive properties of the objects in Figure 4, whereas SIT does. For instance, according to RBC (axis-3) the axis of object A in Figure 4 is a circle and that of object C in Figure 4 a vertical straight line, whereas the difference between both figures is equivalent to the difference between a circle and a rectangle.

According to SIT axes often coincide with superstructures. Therefore we have focused attention on axes in order to compare RBC and SIT. However, axes do not always coincide with superstructures and cross sections do not always coincide with subordinate structures. The superstructures refer to the highest hierarchical components in the simplest representations of objects. That means that superstructures determine the orientations of subordinate structures and not the other way around.

3 From invariance to regularity

In this part we will make some comments on assumptions underlying RBC and SIT. Again we start from RBC and try, from there, to assess the common and distinctive characteristics of both models.

Basic to RBC are the so-called 'nonaccidental properties' (NAPs). These are the properties of the projection of an object that remain invariant under various viewpoints or transformations of the object (Garner, 1970). Because of this invariance, nonaccidental properties, such as parallelism, bilateral symmetry and linearity, are thought to be retinal cues for three-dimensional features of objects (Rock, 1983; Wagemans, 1993). For instance, a straight line on the retina is probably the projection of a straight edge or of an object such as a needle. This we call the 'linearity cue'. The precise length of a retinal straight line is not a NAP but an accidental property as it is not a reliable index for the length of a straight edge or object.

According to Biederman, invariant properties give rise to retinal cues for object features. In contrast, we believe that, insofar as such cues are valid, they are not based on the invariance of properties but on their regularity (Lowe, 1985). We will try to make our view plausible in several steps, with the focus on the linearity cue.

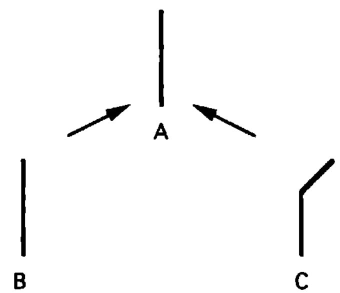


Figure 6. B and C represent three-dimensional objects. A is a possible retinal projection of B or C.

A in Figure 6 represents a retinal straight line, B stands for a three-dimensional needle-like object, and C represents a three-dimensional hook-like object. Apart from the point projection, any projection of a needle is a straight line, such as A in Figure 6 (we disregard the length of this line). Rotation of the needle around its length axis does not change its projection. However, this does not hold for the hook. In fact, the probability that the projection of the hook is a straight line, is infinitely small. Thus, if no other objects than the two objects in Figure 6 are at hand, a retinal straight line is a reliable cue for the presence of the needle. So far, this means that the linearity cue is valid and that this validity can be based on the nonaccidental property of linearity.

A first question concerns the straight-line projection of a hook. We stated that the probability of this projection is infinitely small. Without doubt, this is true in an ontological sense, but not for perception. Any perceptual system has a restricted resolution. It is not able to distinguish slightly different lengths. Nor is it able to distinguish angles that are slightly different. Therefore we assume that by perception a limited number, say L, of lengths and a limited number, say H, of angles can be distinguished. This implies that the probability P, that a hook leads to a retinal straight-line projection, is not infinitely small, but $P = 1/H$. This is called an 'a posteriori' probability, as it deals with the transition from object to image. The a posteriori probability that a needle leads to a retinal straight line is still $P = 1$, and reflects the so-called 'linearity invariance' (Stevens, 1980; Lowe, 1985). However, the validity of the linearity cue depends on the reverse, namely on the transition from image to object (Stevens, 1980; Lowe, 1985). The probability that a retinal straight line stems from the needle is then, according to the Bayes formula, equal to:

$$P = 1/(1 + 1/H).$$

This implies that the linearity cue is still valid in the restricted world of Figure 6, with only two objects.

Now we consider a broader, though still restricted world. It comprises all possible needles and all possible hooks that can be distinguished from a fixed distance. It comprises no more objects and no same objects. In this world, there are L needles, as only L different lengths can be distinguished. As hooks consist of two line segments and of one angle in between, there are in the order of L x H x L hooks. According to the Bayes formula, the probability that a retinal straight line stems from a needle is equal to:

$$P = L/(L + (LxHxL)/H).$$

This implies that a retinal straight line stems about L times more often from a hook than from a needle object. So in this world the linearity cue is completely invalid.

According to Biederman, but also in our view, the linearity cue is in fact valid (Pomerantz & Kubovy, 1986). Suppose that the linearity is based purely on rotation invariance, as shown in the two-object world of Figure 6. This implies that a retinal straight line actually stems about H times more often from a needle than from a hook. Under this supposition the previously considered world of all distinguishable needles and hooks is completely unrealistic. Instead it should comprise as many needles as hooks. As the previous world contains L needles and L x H x L hooks, H x L times more needles should be added to it, or as many hooks should be removed from it. Without this adjustment, the linearity cue would L times more often favour the hook interpretation (see previous paragraph) instead of H times more often the needle interpretation. The adjusted world contains more regular objects than the previous world, because needles are more regular than hooks. As the contribution of regularity to the validity of the linearity cue can be quantified by H x L, and the contribution of invariance by H, regularity is about L times more decisive for the linearity cue than is invariance. Hence, if a retinal straight line is interpreted as a needle and not as a hook, this is less because a needle is rotation invariant, but mainly because there exist many regular objects such as needles (Attneave, 1982).

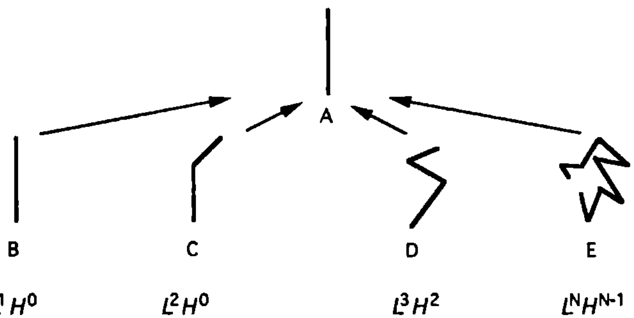


Figure 7. A is a possible projection of all two-dimensional objects (B,C,...,E). Below each object is indicated how many different variants of that object with the same structure can be distinguished. L refers to the number of distinguishable lengths, H to the number of distinguishable angles, N to the number of line segments in the objects, and N-1 to the number of angles in the objects.

With respect to the contribution of invariance to the linearity cue, the contribution of regularity is, in fact, much greater than we have just estimated. All two-dimensional objects can lead to straight-line projections, not only needles and hooks (see Figure 7). Each two-dimensional object, with N different line segments and N-1 angles, has in principle, L^N x H^{N-1} metrical variants with the same structure (Collard & Buffart, 1983). Hence, for adjusting this imaginary world of all such distinguishable objects towards a world that allows a valid linearity cue, innumerably more regular objects, such as needles, have to be added to it than we have estimated before.

By means of Figure 7 a qualitative relation between invariance and regularity can also be established. Only a needle (B in Figure 7) leads to same projections under rotation around its length axis. All other objects (C, D, and E) are equally variant from varying viewpoints. Hence, invariance is an all-or-nothing property. This is not true for regularity. A straight-line object (B) is a highly regular object, but all other objects are not equally irregular. From B to E in Figure 7 the complexity increases and the regularity decreases gradually. Thus only the most regular objects give rise to invariance. So, invariance is just an accidental property of regularity and not basic to regularity.

3.1 *Summary and conclusions*

We have argued that object regularity, not invariance, is primarily decisive for a valid linearity cue. Moreover, we tried to show that invariance is an accidental property of regularity and not the other way around. Regularity gradually varies from low to high, whereas invariance applies only to the most regular instance on this regularity dimension. These inferences are meaningful for SIT and RBC.

According to the minimum principle the simplest, most regular interpretation of a pattern is the perceptually preferred one. However, it depends on the regularity in the real world whether the simplest interpretation is the best bet, i.e. veridical (Perkins, 1976). It is difficult to quantify to what extent the world is regular, but our estimation is that it is, to a great extent, regular, under the plausible assumption that cues, such as the linearity cue, are at least minimally valid.

NAPs are treated as tools for the identification of geons. These NAPs are supposed to have this specific role on the basis of invariance criteria. However, as we have argued, NAPs are not based on invariance but rather on regularity. That implies that a retinal straight line is not interpreted as a needle because of its invariance but because of its regularity. The latter reason is in line with the minimum principle. However, there is no reason to preserve this principle only for highly simple patterns, which accidentally reveal invariant properties, but also to use it for complex patterns, whose interpretations are equally variant under transformations, but not equally regular.

A problem for SIT is to specify the 'size of the stimulus' (Hochberg, 1982) for which the minimum principle applies. For a perceiver, a stimulus is more than a sum of local parts. Almost any part can be embedded in a complex pattern, such that the interpretation of the part without context is absent in the interpretation of the whole pattern. However, we do not know to what extent context affects the interpretation of a pattern (Hochberg, 1982; Kanizsa, 1979; Leeuwenberg & Boselie, 1988). For RBC this issue is rather irrelevant as it assumes, in advance, that the identification of a geon is mediated by cues, such as NAPs, and that a complex object is composed by elementary objects, such as geons.

4 Final remarks

A local bottom-up approach (RBC) is compared with a holistic concept of object perception (SIT). According to RBC scenes are composed by predefined simple objects, called geons. These geons, on their turn, are specified by predefined properties of cross sections and axes. The detection of geons is mediated by viewpoint-independent object properties (NAPs), which are assumed to be invariant under object transformations. According to SIT, perception makes no use of predefined geons and predefined geon properties. Geons and these properties are just a posteriori features of simple object representations, which account for a maximum of regularities in objects. Moreover, NAPs are, according to SIT, not privileged properties that are invariant under transformations, but just accidental effects of the perceptual tendency towards simplest pattern representations.

In section 2 of this paper we considered the role of object axes in perception. According to RBC, an object axis can be straight or circular and is mainly specified by its length. We have attempted to show that these restrictions are not compatible with the perceptual classification of objects. This is not true for SIT. According to the latter approach an object axis can have any structure and is not determined by its length. Instead, an axis is revealed by the simplest object representation, and agrees with the highest hierarchical component of this representation, namely the 'superstructure'. Although this superstructure is not predefined by pattern-independent features, it is well defined. In contrast, the RBC definition of axis agrees with the commonsense notion of axis. This concept of axis is indeed predefined by pattern-independent features, but, in fact, not well defined.

Section 3 deals with viewpoint-independent properties. Argued is that the transformation invariance of these properties is characteristic for the most regular objects, such as linear or symmetrical objects. Moreover we showed that these properties on the retina, in principle, stem rather from irregular than from regular objects in a world that comprises all possible objects. The inference is made that, if such retinal properties are indeed taken as valid cues for regular properties of objects, this validity is based on the abundant presence of regular objects in the real world. Notice that this inference leads to a conclusion about reality on the basis of perception. This conclusion can be considered as a justification of the perceptual tendency towards simplest object representations, i.e. of SIT. An advantage of RBC is that it specifies the way objects are identified from their retinal projections. This is not true for SIT.

"Components by Simplicity"

Chapter 6

In support of structural hierarchy in visual shape

Abstract
The descriptive minimum principle states that the preferred interpretation of a pattern is reflected by the simplest representation of that pattern. Such a simplest representation generally has a hierarchical structure. The pattern component represented at the highest hierarchical level is said to constitute the "superstructure" of the pattern, and pattern components represented at lower levels are said to constitute the "subordinate" structure. The primed-matching paradigm has been employed in two experiments, in order to test whether superstructures of three-dimensional objects are perceptually more dominant than subordinate structures. In the first experiment, the test pairs consisted of two-dimensional line drawings of three-dimensional objects; each prime was a two-dimensional face of such an object, corresponding to either the superstructure or the subordinate structure. Two priming conditions were employed. In the "literal" condition, the object face was presented as it appears in the drawing of the object (physical similarity). In the "frontal" condition, the object face was presented in the frontal-parallel plane (representational similarity). Object matching was found to be facilitated more by priming superstructures than by priming subordinate structures. This differential effect was strongest in the frontal condition. In the second experiment, the order was reversed: the test pairs were composed of the object faces and the object drawings were taken as primes. Again there were facilitating effects for both superstructures and subordinate structures but, this time, without differentiation between superstructures and subordinate structures. This suggests that the results of the first experiment cannot be attributed to differences in the way the parts are embedded in the objects or in the object drawings. We conclude that the data support the proposed structural hierarchy in visual shape.

1 Introduction

This paper deals with the model of object representation that has been developed within the Structural Information Theory (SIT) (Leeuwenberg, 1969, 1971; Leeuwenberg & Van der Helm, 1991). A key assumption of SIT is the global-minimum principle (Hochberg & McAlister, 1953). According to that principle, the simplest of all possible representations of an object is the preferred one. With respect to object representation, this implies that relevant object features cannot be assessed a priori, but are the result of the simplest representation of that object. Leeuwenberg and Van der Helm (1991), and Leeuwenberg, Van der Helm, and Van Lier (1994), demonstrated that these features may have a hierarchical relationship with respect to each other. The topic, however, is not without controversy. For example, Biederman's RBC model (1987) starts from predefined features, such as specific types of axes and cross sections, in the classification of its elementary volumetric components (called "geons"). These predefined features do not have a hierarchical relationship. In previous papers, Leeuwenberg and Van der Helm (1991), and Leeuwenberg et al. (1994), discussed differences between the SIT approach and other approaches such as RBC. In the present study, we focus on the hierarchical relationship between the relevant object features as specified within SIT, and we empirically test its role in object representation. We will not go into the formal details of SIT (for such details see Leeuwenberg & Van der Helm, 1991; Van der Helm & Leeuwenberg, 1991; Van der Helm, Van Lier, & Leeuwenberg, 1992; Van Lier, Van der Helm, & Leeuwenberg, 1994, 1995). For the relatively simple stimulus objects to be considered in the present paper, the following demonstrations suffice.

The tube-like object in Figure 1A has a global S-shaped form and a constant circular cross section. In fact, the exterior shape of this object can be mimicked exactly by moving a circle orthogonally along an S-shaped curve (see Figure 1B). Now, SIT's resulting representation of this tube-like object precisely comprises the S-curve and the circle as separately represented object components, plus the relation between these components. This relation, analogue to "moving one along the other", is a hierarchical relation: the S-curve specifies the positions and orientations of the circles, not the other way around. Therefore, the S-curve is called the "superstructure" of the object, and the circle is called its "subordinate" structure. Figure 1B' shows a visualization of SIT's representation of the tube-like object, indicating the relation between the separately represented components by depicting the subordinate-structure component below the superstructure component. The hierarchical character of the super-subordinate relation may be illustrated further by Figure 2. SIT's resulting representation of the vase-like object in Figure 2A again comprises an S-curve and a circle as separately represented object components, but this time their relation is analogue to moving the S-curve along the circle (see Figure 2B). Therefore, for this object, the circle is the superstructure and the S-curve is the subordinate structure (see Figure 2B'), which is the reverse of the hierarchy in Figure 1B'. This illustrates the impact of the hierarchical relation between components: two representations comprising the same separately represented object components may, due to differences in hierarchy, yet represent completely different objects.

Evidently, many other representations are possible for the objects in Figures 1 and 2. As mentioned, an important assumption within SIT is the global-minimum principle, which prescribes that the simplest of all possible interpretations of a shape is preferred. SIT's simplicity demand may be illustrated by Figures 1C and 2C showing visualizations of alternative interpretations of the tube-like object and the vase-like object. The representations (Figures 1C' and 2C') of these alternative interpretations comprise the specification of many different components and many different relations between components. Compare for example the difference between the S-shapes that are needed to describe the left side and the right side of the tube in Figure 1C. These alternative interpretations contrast with the earlier discussed interpretations (Figures 1B and 2B) for which the representations (Figures 1B' and 2B') comprise the specification of only two components and one relation between those two components. Clearly, the

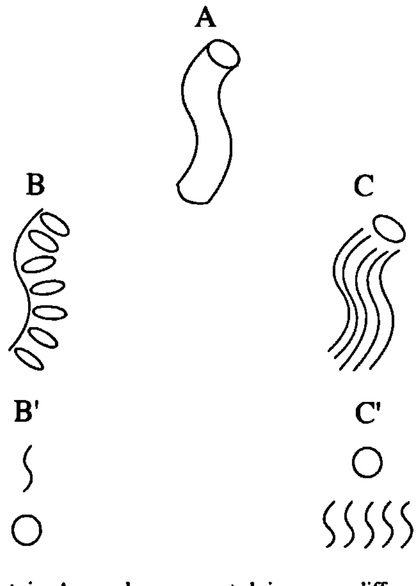


Figure 1. The tube-like object in A can be represented in many different ways. B and C show two possible ways to mimic the exterior shape of the object, reflecting the meaning of the hierarchical representations in B' and C', respectively. The representation in C' is rather complex, as it comprises many different components. The representation in B' comprises only two components (an S-curve and a circle), and is the simplest representation of the object. Therefore, the higher-hierarchical component in B' (the S-curve) is the superstructure of the object, and the lower-hierarchical component in B' (the circle) is its subordinate structure.

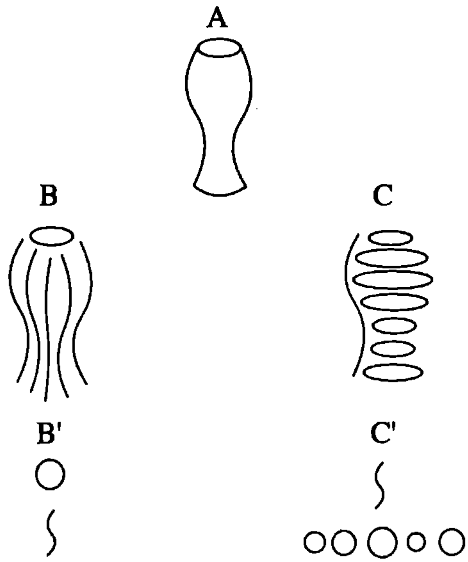


Figure 2. The vase-like object in A can be represented in many different ways. B and C show two possible ways to mimic the exterior shape of the object, reflecting the meaning of the hierarchical representations in B' and C', respectively. The representation in C' is rather complex, as it comprises many different components. The representation in B' comprises only two components (a circle and an S-curve), and is the simplest representation of the object. Therefore, the higher-hierarchical component in B' (the circle) is the superstructure of the object, and the lower-hierarchical component in B' (the S-curve) is its subordinate structure. This hierarchy is the reverse of the hierarchy in Figure 1B'.

latter representations are much simpler. In fact, they are the simplest representations of those objects and, therefore, determine the superstructure and the subordinate structure of those objects.

The S-shaped superstructure of the object in Figure 1A can be characterized as a global structure and roughly corresponds with the low-spatial-frequency structure. Such a correspondence might be expected in the context of Navon's (1977) global-precedence approach (see also Leeuwenberg & Van der Helm, 1991). Notice, however, that this is not always the case. For example, the low-spatial-frequency structure of the vase-like object in Figure 2A, is determined mainly by the two symmetric outer S-curves, whereas SIT's superstructure is given by a circle.

SIT's hierarchical approach shares some aspects with Biederman's RBC model, but there are also essential differences. The RBC model integrates ideas of many other scientists (e.g. Barrow & Tenenbaum, 1982; Binford, 1981; Garner, 1962; Navon, 1977; Marr, 1982; Hoffman & Richards, 1985) and, despite the opposition against it (e.g. Leeuwenberg & Van der Helm, 1991; Leeuwenberg, Van der Helm, & Van Lier, 1994;

Kurbat, 1995), it can be seen as a prototypical approach within current theorizing on object recognition. RBC allows only geon axes that are straight or monotonously curved (i.e. without points of inflection). Because of that, RBC would decompose the tube-like object in Figure 1A into two geons: the upper half and the lower half of that object. The combined curved axes of these two geons form an S-curve, corresponding to the S-curve which, according to SIT, constitutes the superstructure of the object. SIT's superstructure, however, does not necessarily correspond to RBC's axis. For the vase-like object in Figure 2A the situation is different. As RBC allows only geon cross sections that either expand or contract, or first expand and then contract, this object also consists of two geons: the part above and the part below the smallest cross section of that object. These parts each have a straight axis and a varying circular cross section. So, this time, SIT's superstructure (a circle) corresponds to the geon cross section. Within RBC there is no representational difference between the cross section of the object in Figure 1A and the cross section of the object in Figure 2A, whereas within SIT that circular component is represented once as a subordinate structure (Figure 1A), and once as a superstructure (Figure 2A).

2 Superstructure-dominance hypothesis

An important aspect of SIT's model of object representations is the hierarchical dependency relation between the separately represented object components. As indicated, the superstructure determines the positions and orientations of the subordinate structures, not the other way around. We therefore hypothesize that the superstructure is perceptually more dominant than its subordinate structures. SIT's hierarchical approach and the superstructure-dominance hypothesis have already gained some support. As illustrated in section 1, SIT's approach allows any pattern component to emerge as superstructure, provided that it yields maximal representational simplicity. Leeuwenberg et al. (1994) demonstrated that this approach accounts better for object classification than does the RBC approach, which allows only a few types of axes and cross sections. Furthermore, Leeuwenberg and Van der Helm (1991) demonstrated how the super-subordinate hierarchy can be related to perceived unity and variety of patterns. An experiment (Van Bakel, 1989) supported this hypothesis for three-dimensional objects. In that experiment subjects were asked to judge whether a presented pair of objects was perceived as unitary or as dual. For the specific stimulus set used, it appeared that a pair of objects with the same superstructure was more likely perceived as unitary than was a pair of objects with the same subordinate structure (see Leeuwenberg & Van der Helm (1991) for a synopsis of Van Bakel's study). We view that experiment, however, as a rather indirect test of the superstructure-dominance hypothesis as it uses the intermediate concepts of unity and variety. The purpose of this paper is to present a more direct test of the relative strength of superstructures and subordinate structures of three-dimensional objects, by means of the primed-matching paradigm.

3 Primed-matching paradigm

In the primed-matching paradigm, the effect of a prime on matching a pair of shapes is tested. Beller (1971) found that, in the case of a matching test pair (two identical shapes), the responses are facilitated by representational similarity of prime and test shapes. That is, to give the gist of it, matching the letters in the pair "aa" is not only facilitated by the physically similar prime "a", but also by the representationally similar prime "A". The primed-matching paradigm has recently gained renewed attention by its application in the domain of visual occlusion and completion. Sekuler and Palmer (1992) used partly occluded two-dimensional shapes as primes, and unoccluded two-dimensional shapes in the test pairs. In the case that both test shapes corresponded to the preferred completion of the occluded shape in the prime, they found a higher facilitating effect than in the case that both test shapes corresponded to the literal "mosaic" interpretation. This result suggests that the facilitation can be explained better by the representational similarity of the activated interpretations of prime and test shapes than by the physical similarity of prime and test shapes. Other studies confirmed these findings for a broader range of occlusion patterns (Sekuler, Palmer, & Flynn, 1994; Sekuler, 1994; Van Lier, Leeuwenberg, & Van der Helm, 1995). In the present study, the distinction between physical similarity and representational similarity is taken into account in testing the superstructure-dominance hypothesis for three-dimensional objects. Our hypothesis is that the matching of two identical objects is facilitated more by priming their superstructures than by priming their subordinate structures.

4 Experiment 1

4.1 *Subjects*

Thirty-one subjects participated in the experiment. All subjects received a small payment.

4.2 *Stimuli*

In Figure 3 all stimulus objects are shown, together with a visualization of SIT's representation of each object. The objects were constructed in the way indicated in Figures 1B and 2B. Objects A, B, C, and D (set 1) were constructed by means of a circle plus a C-shaped or an S-shaped curve. The circle corresponds with the superstructure in objects A and B, and with the subordinate structure in objects C and D. Objects E, F, G, and H (set 2) were constructed by means of a square plus a C-shaped or an S-shaped curve. The square corresponds with the superstructure in objects E and F, and with the subordinate structure in objects G and H. With these objects, 8 different matching test pairs were composed. In order to balance the amount of correct same/different answers, 8 nonmatching test pairs were included as well. These non-matching test pairs were composed such that all objects were presented an equal number of times.

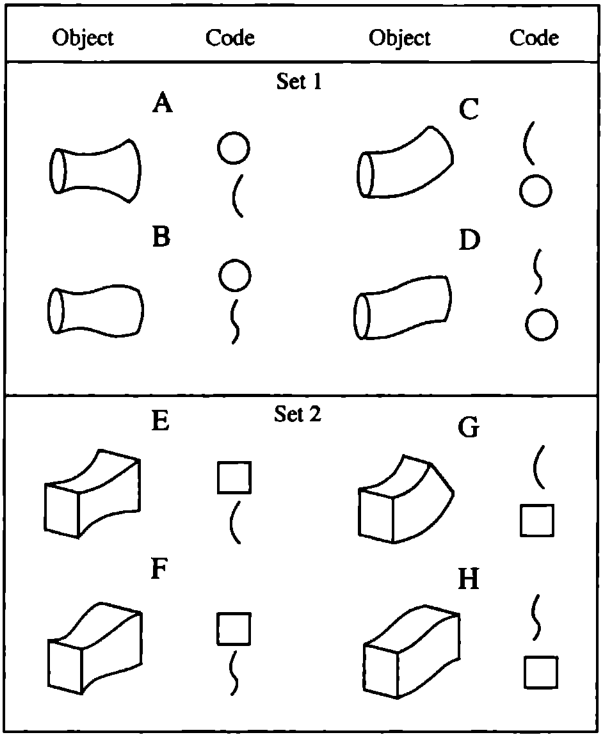


Figure 3. All objects that were used in the experiments, together with the representation of each object. The objects were constructed by means of a C-shaped or an S-shaped curve, plus a circle (set 1) or a square (set 2). In the drawings, the physical appearance of all circles in set 1 and of all squares in set 2, is the same. In the left-hand column the circles and the squares are the superstructures of the objects; in the right-hand column they are the subordinate structures of the objects.

The primes were constituted by the circle and the square. Two priming conditions were employed: a "literal" priming condition and a "frontal" priming condition (see Figure 4). In the literal priming condition, the object component was presented exactly as it appears in the drawing of the object (an ellipse or a parallelogram). This implies that there is physical similarity between the prime component and the corresponding object component in the test shapes. In the frontal priming condition the object component was presented as it would appear in the frontal-parallel plane (circle or square). The prime now corresponds to the representation of that object component, so that there is representational similarity between the prime component and the corresponding object component in the test shapes. In principle, one could use both the superstructure and the subordinate structure of each object as a prime. This would, however, create several control problems. For instance, the circle and the square are two-dimensional object faces, whereas the C-curve and the S-curve are not, which would undermine the comparability of the primes. Moreover, the literal appearances of the C-curves and S-curves in the object drawings all differ. Since such problems do not arise for the circle and the square, the literal and frontal versions of only these two-dimensional object faces were taken as primes. As a control also a no-prime was included (represented by the letter 'x'), so that there were 5 different primes. The choice of the primes implies that one cannot test the relative strength of the superstructure and the subordinate structure within one object. But these strengths can yet be tested by comparing the priming effect of a component on matching objects in which it is the superstructure, with the priming effect on matching objects in which it is the subordinate structure.

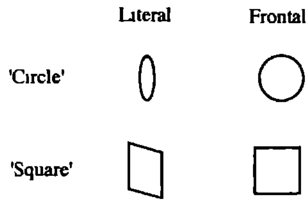


Figure 4. The circular and square-like object components used in the experiments. The literal version is the object component as it appears in the drawing of the objects (see Figure 3). The frontal version is the object component presented in the frontal parallel plane.

4.3 *Procedure*

In Figure 5 the sequence of events in one experimental trial is shown. First, a fixation dot was presented for 500 ms (in all trials, at the same position on a computer screen). Then, after a blanc of 50 ms, the prime was presented at the same position as the fixation dot. The presentation time of the prime was 500 ms, which is long enough to ensure a strong activation of the representation of the prime shape (see e.g. Sekuler & Palmer, 1992). The test pair was presented 17 ms after the prime had disappeared. The visual angle of the prime was about 2°, and the visual angle of the test pair was about 7°. The subjects were instructed to respond as quickly as possible, as a maximum, a response time of 2500 ms was allowed. To encourage the subjects to respond quickly, the subjects received visual feedback on their response time after each trial (in concordance with Sekuler & Palmer, 1992, and Van Lier et al., 1995). Wrong answers were also reported to the subjects, and those trials were presented once more in a later stage of the series of trials. In order to control for possible orientation effects, each combination of prime and test pair was presented twice: once in the orientation as given in Figures 3 and 4, and once 90 degrees rotated in clockwise direction. Each subject was instructed with a series of 15 trials.

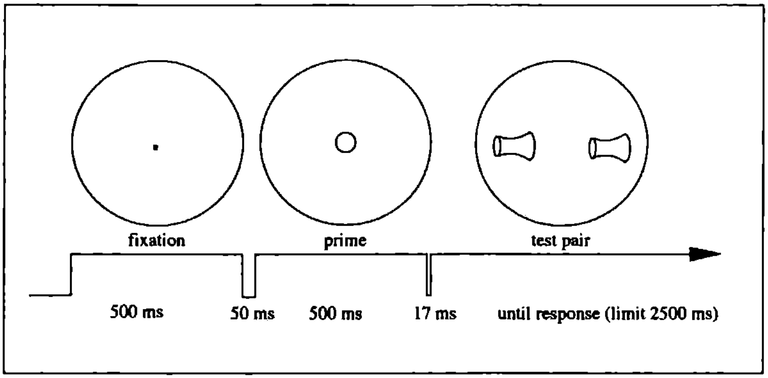


Figure 5. The spatial and temporal layout of the experimental procedure in Experiment 1.

4.4 *Results*

In the analysis, the response times on the test pairs after the no-prime are taken as baseline values. That is, for a specific prime, its priming effect (PE) on a matching test pair is defined by the response time on this test pair after the no-prime minus the response time on this test pair after that specific prime. In this way, possible differences in processing speed between test objects are accounted for. As we are interested in facilitation, we consider all trials in which the objects of the test pair are identical, and, moreover, in which the prime corresponds to a (literal or frontal) face of those objects. Table 1 shows the mean response times and the priming effects. In the literal priming condition, the priming effects of both the superstructure primes and the subordinate-structure primes are significant, whereas in the frontal priming condition only the superstructure primes yield a significant priming effect (the t-values are given in Table 1).

An analysis of variance (ANOVA) with PE as the dependent variable has been performed on the following factors: Structure (super versus subordinate), Projection (literal versus frontal), and Set (circle versus square). Both the main effect on Structure ($F(1,30)=5.43$, $p<0.05$) and the main effect on Projection ($F(1,30)=10.01$, $p<0.01$) are significant. The main effect on Set is not significant ($F(1,30)=1.30$). There are no significant interaction effects on Structure x Set ($F(1,30)=0.00$), Structure x Projection ($F(1,30)=0.74$), and Set x Projection ($F(1,30)=1.41$). The three-way interaction Structure x Set x Projection is not significant either ($F(1,30)=0.01$). In Figure 6, the mean PE values are shown for the literal primes and the frontal primes. The difference in priming effect between superstructure primes and subordinate-structure primes is not significant ($t(30)=1.59$) in the literal priming condition, whereas it is significant ($t(30)=2.46$, $p<0.05$) in the frontal priming condition. In Figure 7, the data are given for each set (circles and squares) separately.

	RT_{Prime} (ms)	$RT_{No\text{-}prime}$ (ms)	PE (ms)	t(30)	
			Literal		
Superstructure	714.4	792.6	78.2	5.00	$p<0.001$
Subordinate Structure	735.4	777.7	42.3	2.30	$p<0.05$
			Frontal		
Superstructure	742.5	792.6	50.1	2.86	$p<0.001$
Subordinate Structure	782.7	777.7	-5.0	0.33	n.s.

Table 1. Results of Experiment 1. In the first column the mean response times are given for the trials in which the literal or the frontal prime component was either the superstructure or the subordinate structure of the matching test objects (RT_{Prime}) In the second column the response times on the no-prime trials are given ($RT_{No\text{-}Prime}$) In the third column the priming effects (PE) are given, being the response times of the second column minus the response times of the first column In the fourth column the t-values are given for each priming effect.

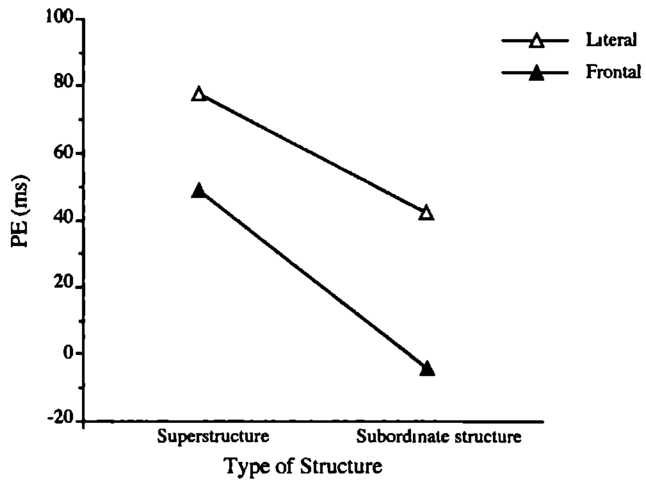


Figure 6. Results of Experiment 1. The mean priming effects (PE) of the literal and frontal prime components on matching test objects in which either the superstructure or the subordinate structure corresponded to the prime

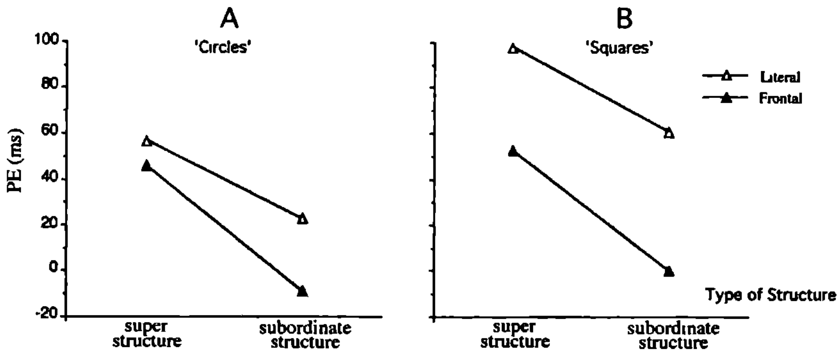


Figure 7. Results of Experiment 1. The mean priming effects (PE) of the literal and the frontal prime circles (A) and of the literal and the frontal prime squares (B) on matching test objects in which either the superstructure or the subordinate structure corresponded to the prime.

4.5 *Discussion*

In both the frontal priming condition and the literal priming condition, the priming effects were higher for the superstructures than for the subordinate structures. The difference in priming effect between superstructures and subordinate structures is significant in the frontal priming condition, and almost significant in the literal priming condition. The main effect on Structure supports the superstructure-dominance hypothesis. Yet, the main effect on Projection calls for further discussion. It appears that the priming effects for both the superstructures and the subordinate structures are higher in the literal priming condition than in the frontal priming condition. In our view this can be understood as follows. In the frontal priming condition, the physical similarity between the prime component and the corresponding components in the test objects obviously is very small, whereas the representational similarity is large. Consequently, in the frontal priming condition, the representational similarity is the decisive facilitation factor, and the hierarchy in the representations assigns a dominant role to the superstructures. In the literal priming condition, the physical similarity between the prime component and the corresponding components in the test objects is large for both the superstructures and the subordinate structures. In addition to that, there is also substantial representational similarity, as in the present 3D context the literal primes (ellipse and parallelogram) are readily perceived as their prototypes (circle and square, respectively). Thus, in the literal priming condition, there are two relevant facilitation factors. First, the physical similarity which has about equal effect for superstructures and subordinate structures and, second, the representational similarity which differentiates (though not as strong as in the frontal priming condition) between superstructures and subordinate structures. Note that the representational similarity between the literal primes and the test shapes is much more relevant than the physical similarity between the frontal primes and test shapes.

We now examine some alternative explanations for the difference in the priming effects. It should be realized that the tested objects may also be differentially classified by other approaches such as RBC. Indeed, also according to the RBC approach, there are systematic differences between the objects used in our experiments. For instance, objects A, B, E, and F in Figure 3 (the objects in which the test component is a superstructure) are constituted by geons with a straight axis and a varying cross section, whereas objects C, D, G, and H in Figure 3 (the objects in which the test component is a subordinate structure) are constituted by geons with a curved axis and a constant cross section. However, this different RBC classification as such cannot be an explanation for the different priming effects. Also if RBC would hypothesize a difference in representational status between axis and cross section, rendering for example the axis more dominant than the cross section (which would be more or less in line with Navon), it still would not explain the different priming effects in Experiment 1.

It could be argued that the redundancy of the cross section in the objects caused the difference in the priming effects. As indicated, in the objects in which the cross section is a superstructure, the cross section varies in size, whereas in the objects in which the cross section is a subordinate structure, the cross section has a constant size. Note further that the difference in curvature of the axis leaves the angle between axis and cross section constant for both classes of objects. Considering the constancy of the cross section in the objects in which it is a subordinate structure, that specific cross section is far more redundantly present in those objects than it is in the objects in which it is a superstructure. On the basis of that, a dominant role of the cross section even would seem to be more likely in the objects in which it is a subordinate structure. Yet, according to the results of Experiment 1, the opposite is the case.

There is yet another possible explanation for the difference in the priming effects. It might be that, in the objects or in the object drawings, the embeddedness of the superstructures somehow differs from the embeddedness of the subordinate structures. In the stimulus construction we have tried to reduce such a difference. For example, in the drawings of the objects, the ellipse and the parallelogram are connected to the same number of other contour lines at exactly the same positions both for the objects in which they coincide with the superstructure, and for the objects in which they coincide with the subordinate structure. The angles of connections, however, inevitably vary between objects. Such a difference in embeddedness, caused by small metric variations, could render the superstructures more salient so that, independently of an object's representational hierarchy, its superstructure is primed more easily. To be clear, this effect would not be caused by the prime component but by the primed component. In order to control for this effect, we have performed a second experiment in which the objects were presented first. That is, instead of taking the components as primes and the objects as test shapes, now the objects were taken as primes and the components as test shapes. Then, components that are more saliently embedded in the primes are predicted to be detected more easily (cf. Reed, 1974; Reed & Johnsen, 1975) and are expected to have a higher priming effect than less saliently embedded parts. Thus, on the basis of embeddedness, one would expect the same difference as was found in Experiment 1. In a further section, we will argue that this is not to be expected if hierarchy is the cause for the differential effect in Experiment 1.

5 Experiment 2 (Control experiment)

5.1 *Subjects*

The subjects who participated in the previous experiment, participated again in this experiment. They received a small payment.

5.2 *Stimuli*

The 8 test objects of Experiment 1 were now used as primes, yielding, together with a no-prime, 9 different primes. The prime components of Experiment 1 were now used to compose the test pairs. Analogue to Experiment 1, two test conditions were employed: a literal test condition with the literal versions of the components, and a frontal test condition with the frontal versions of the components. This yields 4 different matching pairs. In order to balance the amount of correct same/different answers, 4 nonmatching test pairs were included as well. These nonmatching test pairs were composed such that all test components were presented an equal number of times.

5.3 *Procedure*

The procedure was the same as in Experiment 1. See Figure 8 for an example of the reversed presentation order of objects and components.

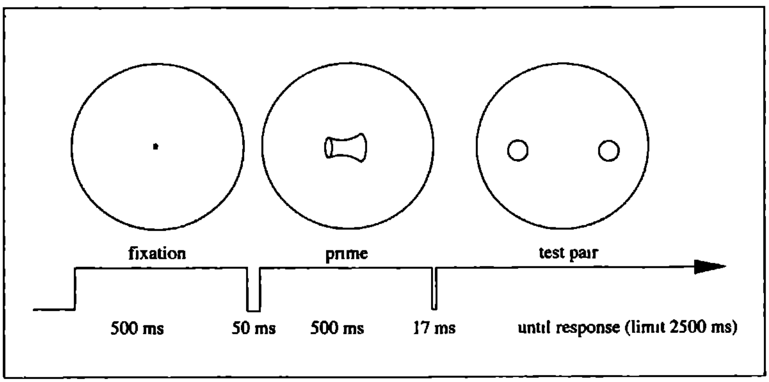


Figure 8. The spatial and temporal layout of the experimental procedure in Experiment 2.

5.4 *Results*

Again, the response times on the test pairs after the no-prime will be taken as baseline values (see Experiment 1), and we will consider those trials with matching test components that correspond to either the superstructure or the subordinate structure of the prime object. Table 2 shows the mean response times and the priming effects. All priming effects are significant (the t-values are given in Table 2), i.e. in both the literal test condition and the frontal test condition, the prime objects facilitate matching the test components, no matter whether the test components correspond to the superstructure or to the subordinate structure of the prime object.

	RT_{Prime} (ms)	$RT_{No\text{-}prime}$ (ms)	PE (ms)	t(30)
		Literal		
Superstructure	503.8	564.6	60.8	3.69 $p<0.01$
Subordinate Structure	519.0	564.6	45.6	2.71 $p<0.05$
		Frontal		
Superstructure	485.8	515.4	29.6	3.30 $p<0.01$
Subordinate Structure	481.5	515.4	33.9	4.33 $p<0.001$

Table 2. Results of Experiment 2. In the first column the mean response times are given for the trials in which the literal or the frontal matching test components were either the superstructure or the subordinate structure of the prime object (RT_{Prime}) In the second column the response times on the no-prime trials are given ($RT_{No\text{-}Prime}$). In the third column the priming effects (PE) are given, being the response times of the second column minus the response times of the first column. In the fourth column the t-values are given for each priming effect.

An analysis of variance (ANOVA) with priming effect PE as dependent variable has been performed on the same factors as in Experiment 1: Structure (super versus subordinate), Projection (literal versus frontal), and Set (circle versus square). There are no main effects on Structure ($F(1,30)=0.39$), Projection ($F(1,30)=1.50$), and Set ($F(1,30)=0.10$). There are no significant interaction effects on Structure x Set ($F(1,30)=0.49$), Structure x Projection ($F(1,30)=1.54$), and Set x Projection ($F(1,30)=0.04$). The three-way interaction Structure x Set x Projection is not significant either

(F(1,30)=1.22). Figure 9 shows the mean priming effects in the literal and the frontal test conditions. Neither in the literal test condition nor in the frontal test condition there is a significant difference between, on the one hand, the priming effects on the test components that correspond to the superstructure, and, on the other hand, the priming effects on the test components that correspond to the subordinate structure (t(30)=0.43 and t(30)=0.261, respectively). In Figure 10, the data are given for each set (circles and squares) separately.

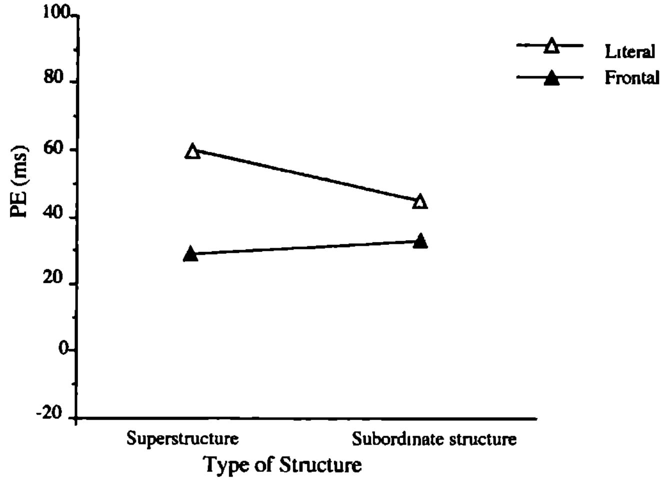


Figure 9. Results of Experiment 2 The mean priming effects (PE), on matching literal or frontal test components, of the prime objects in which either the superstructure or the subordinate structure corresponded to the test components

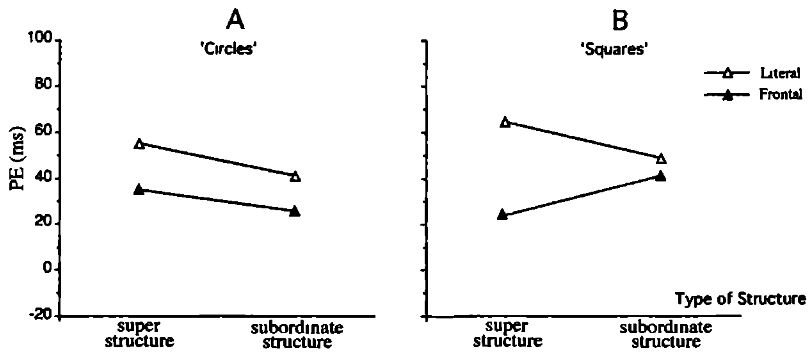


Figure 10. Results of Experiment 2. The mean priming effects (PE), on matching literal or frontal test circles (in A) and test squares (in B), of the prime objects in which either the superstructure or the subordinate structure corresponded to the test components.

5.5 *Discussion*

For each Structure x Projection combination the priming effect is significant. However, this time, there are no significant differences in priming effects between superstructures and subordinate structures, neither in the literal test condition nor in the frontal test condition. We reasoned that if a difference in embeddedness is the only or main cause of the differential effects between superstructures and subordinate structures in Experiment 1, this differential effect should also be observed in Experiment 2. Clearly this is not the case. Yet, one could argue that differences in detectability caused by embeddedness, faded away because of the relatively long presentation times of the objects (being 500 ms in our case). However, this argument does not seem to be very plausible. For example, with presentation times of 1000 ms for the whole pattern, Reed (1974) still found detectability differences caused by embeddedness in a whole-part detection task. Additionally, Reed and Johnsen (1975) found a significant correlation ($p<0.01$) between the response times on a part-whole detection task and the response times on a whole-part detection task (with the same wholes and parts). The difference in the main effect on Structure between Experiments 1 and 2 suggests that such a congruence does not hold for the present results. In fact, the Pearson's correlation coefficient for the mean PE values of Experiment 1 and Experiment 2 is far from significant for both the literal condition and the frontal condition ($r=0.16$ and $r=-0.06$, respectively). It is also noticeable that Reed and Johnsen (1975) found that subjects performed better in the part-whole order than in the whole-part order. This finding has been replicated several times (e.g. Ankrum and Palmer, 1991). Now, if we consider the subordinate structures in the frontal conditions of Experiments 1 and 2, the opposite seems to be the case, i.e. in the first experiment (from part to whole) the priming effect is much smaller than in the second experiment (from whole to part).

All in all the above findings support the conclusion that the differences in response time between superstructure and subordinate structures in Experiment 1 are not caused by a difference in embeddedness but by another factor. As we will argue next, the differential priming effects can be explained by the proposed structural hierarchy within object representations.

6 General discussion

With respect to Experiment 1 we argued that, in the frontal priming condition, representational similarity is the only, or in any case the most dominant, facilitating factor, whereas in the literal priming condition both representational similarity and physical similarity are relevant facilitating factors. The same argument applies to Experiment 2. In our view, the difference between the two experiments is that in Experiment 1 the representational hierarchy differentiates between superstructures and subordinate structures, whereas in Experiment 2 it does not. We will exemplify this view below.

In Experiment 1, the matching of two test objects occurs on the basis of the simplest representations of the objects. Hierarchy is an important property of those simplest representations. Although any part of an object is represented just as easily as any other part, getting the simplest representation of the whole object means selecting the separate representations of specific object parts in a specific hierarchical order, i.e. the parts and the order that yield maximal simplicity. The superstructure is not only one of those specific parts, but also the first one to be selected in order to get that specific hierarchical order. Therefore, a superstructure prime facilitates the search for the simplest representations of the objects and, thereby, facilitates the matching of the objects. In contrast, a subordinate-structure prime perhaps corresponds to one of those specific object parts, but it is not facilitating as it suggests a wrong hierarchical order (like the hierarchical orders in Figures 1C' and 2C'). This explains the absence of a priming effect of the subordinate structure primes in the frontal condition in Experiment 1.

In Experiment 2, before two test components are matched, the simplest representation of the prime object is already available (as indicated, the presentation time of the primes is long enough to ensure this). Now, note that the structural hierarchy enables representations that are simpler than representations without hierarchy. So, the meaning of hierarchy lies in the simplicity of the representation and once that representation is available, hierarchy has done its job and can be dismissed. What remains is a segmentation of the object into equally accessible parts (which justifies Experiment 2 to be a pure embeddedness test). This explains, in our view, that in Experiment 2 hierarchy is not a differential factor, so that the priming effects on superstructures and subordinate structures become about equally strong.

The above view implies that hierarchy is an internal affair of representations, without external implications. As indicated, the hierarchical difference between superstructures and subordinate structures can be assessed during the generation of a representation, but afterwards all parts are equally accessible. As a metaphor, consider the internal and external appearance of the walls of a building: inspecting the internal construction of a building, it may appear that only a few walls are supporting walls, yet each brick equally contributes to the shape of the building.

One further indication can be given in support of our hierarchy explanation. As argued, in the literal conditions, both representational similarity and physical similarity are relevant facilitation factors, whereas in the frontal conditions only representational similarity is a relevant facilitation factor. Therefore, it is to be expected that the presence or absence of hierarchy differentiation is relatively more influential in the frontal conditions than it is in the literal conditions. This can be investigated by analyzing the two experiments within one design. To investigate interactions between Experiment 1 and Experiment 2, the differences in the priming effects between the two experiments can be determined, for each subject and for each of the four Structure x

Projection combinations. These differences reflect the differential effect of the presentation order: from part to wholes versus from whole to parts. In Figure 11, the mean δPE values, defined by PE(Exp1)-PE(Exp2), have been plotted for each of the four Structure x Projection combinations. The difference, in δPE, between superstructures and subordinate structures is not significant for the literal conditions ($t(30)=0.82$), whereas it is significant for the frontal conditions ($t(30)=2.70$, $p<0.05$). This confirms the above expectation that the presence or absence of hierarchy differentiation is relatively more influential in the frontal conditions than it is in the literal conditions.

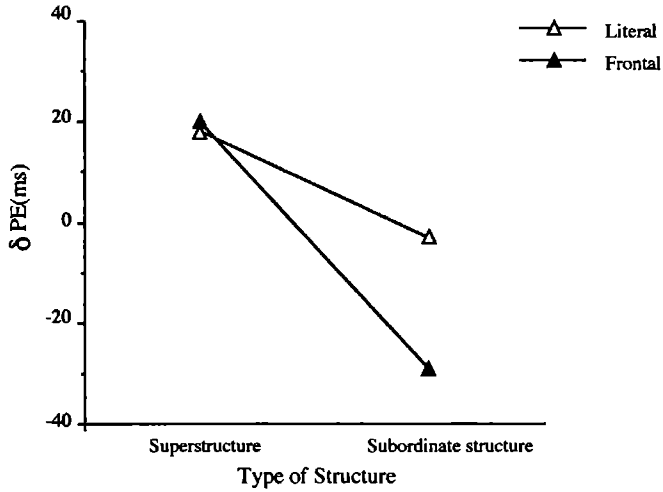


Figure 11. The mean δPE values, defined by PE(Exp1)-PE(Exp2), are given for the literal and frontal components being either the superstructure prime or the subordinate-structure prime in Experiment 1, or the superstructure or subordinate structure of the prime objects in Experiment 2.

7 Conclusion

The data favour the view that superstructures are perceptually more dominant than subordinate structures. This dominance reflects an internal aspect of an object representation and plays a role in the search for the simplest representation of an object. Once a representation is available all components within the organization of an object are equally accessible. The provided support for the superstructure dominance strengthens the notion of structural hierarchy in visual shape as proposed within SIT.

EPILOGUE

1 Introduction

The main issue in this thesis was the overall tendency of the visual system towards the simplest interpretation. The topics that have been dealt with were clustered in four sections (quantification of simplicity, unification by simplicity, diversity by simplicity, components by simplicity). In the introductory chapter of this thesis we posed four objectives in order to seek support and converging evidence for the SIT assumptions. These objectives were: replying to drawbacks of the SIT coding language; reinterpreting demonstrations conflicting with SIT; comparing SIT to alternative approaches; testing specific SIT predictions. These objectives, however, were not treated explicitly in this thesis. Therefore, in this epilogue we recapitulate them in relation to the topics that have been dealt with. Additionally, we will elaborate on a few topics which have not been considered in this thesis, but which are related to this research.

2 Replying to drawbacks of the SIT coding language

Before we will discuss several objections that have been raised with respect to the coding language, we first recall a distinction that has been made in the introductory chapter dealing with two different aspects of the coding language, namely its syntax and its semantics. The syntax concerns the reduction of an initial symbol series to a final minimum code. The semantics concerns the representation of a pattern by a symbol series.

2.1 *Syntax*

In Chapter 1 the formalism of the coding language, proposed by Van der Helm and Leeuwenberg (1986, 1991), has been reviewed. As mentioned in the introductory chapter, Van der Helm and Leeuwenberg (1986, 1991) responded to the criticism that the minimum principle would be unrealistic, by proving that the simplest code can be found without generating every possible code separately. Additionally, the accessibility criterion, specified by the concepts of holographic regularity and transparent hierarchy, provided a justification for the choice of regularities employed within SIT. The same criterion inspired the proposal of the I_{new}-load (Chapter 1) by which parameters at all hierarchical levels in a code are taken into account in order to assess the complexity of that code.

The minimum code does not necessarily express all identities in a pattern. This is a direct consequence of the specific coding language, which allows only specific combinations of regularities within one code. This loss of identities might be considered as a drawback of the coding system. However, it should be noticed that demanding the description of all identities within one code would evolve in template codes without any classifying effects. As a matter of fact, the description of subsets of identities is essential for the classification of patterns (cf. Collard & Buffart, 1983). Yet, nondescribed identities may have a perceptual role as well, as their description allows alternative interpretations of the same pattern. Reconsider, for example, the encodings of the series 'aaba' (Chapter 1). This series can be expressed by the identity structure {1=2, 2=4}. The series can be reduced to the minimum code 'aS[a,b]', expressing the identity {2=4}. Another possible minimum code is '2*(a)ba', expressing the identity {1=2}. In neither case all possible identities are accounted for. Because of this "incompleteness", Collard and Buffart (1983) posed the principle of complementarity. This principle holds that identities which remain unexpressed in a minimum code are expressed in complementary codes revealing different interpretations of the same pattern. The perceptual relevance of such alternative codes has been demonstrated in various experiments (Mens, 1988).

We conclude that the syntax of encoding within SIT has made considerable progress in recent years. Research has led to a new conception of the nature of the regularities that account for pattern interpretation. Future research may shed more light on the impact of the nature of these regularities. In section 4.4 we will elaborate a little further on that.

2.2 *Semantics*

Representing a visual pattern by means of a symbol series causes loss of information. For instance, identities that are present in the pattern may not be transferred to the primitive symbol series. In Chapter 2, for example, the determination of the complexity of the internal structure of an interpretation proceeded by means of tracing the contour of the shape. Contours contain much specific information about the shape (Leeuwenberg, 1971), yet it can be questioned whether contours provide all relevant information. For instance, the primitive code does not reveal closedness of a surface. In the encoding procedure of Chapter 2, this closedness was accounted for to a certain extent by allowing a cyclic encoding, by which any possible starting point on the contour is considered.

Although certain shape characteristics are not explicitly captured by contour tracing, a contour code may implicitly reveal their consequences. Such a shape characteristic is, for example, the concavity or convexity of angles. It has been demonstrated that shapes are more likely segmented at concavities (e.g. Baylis & Driver, 1995; Hoffman & Richards, 1984; Boselie, 1994). So, concave angles seem to have a different perceptual role than convex angles. Before illustrating possible structural accounts, we first mention a metric account (Leeuwenberg, 1978) of the difference between a segmentation at convex angles and a segmentation at concave angles. This difference concerns the total degree of angular turns in the contour code. As each angular turn must be in the same direction (for example anti-clockwise), any closed surface with only convex angles obviously has a total angular turn of 360 degrees. Any additional concave angle in the contour increases this total angular turn. Therefore, a segmentation at concave angles into convex segments always implies that the total angular turn of each segment is smaller than the total angular turn of the nonsegmented concave shape. This is not true for a segmentation at convex angles.

In addition to such a metric account for segmentation at concavities, in specific cases such a segmentation is implicitly accounted for by the tendency towards structural simplicity as well. To illustrate this, consider patterns A and B in Figure 1. Both drawings, considered as two-dimensional patterns, can be segmented into the same two triangles (see A' and B', in Figure 1), yet the suggested segmentation seems to be more compelling for pattern B than for pattern A. Apparently, the concave angle in pattern B supports and facilitates that segmentation. Now, consider the perceptual complexities of these interpretations. Evidently, $I_{internal}$ for the two-triangles (or mosaic) interpretation is the same for both patterns. However, $I_{external}$ of interpretation A' is higher than that of interpretation B' (being 6 and 5, respectively). Thus the total perceptual complexity (I_{total}) for the mosaic interpretation is lowest for pattern B. This, however, is not the reason why the segmentation is more compelling for pattern B. Instead of making such an inter-pattern comparison, each mosaic interpretation should be compared with the alternative intra-pattern interpretations. Consider therefore interpretations A'' and B'' in Figure 1. Both interpretations reflect the so-called envelope interpretation as proposed in Chapter 2. The values of $I_{internal}$ and $I_{external}$ for these interpretations are 8 and 4 for interpretation A'', and 10 and 5 for interpretation B'', so, I_{total} for the alternative envelope interpretation is highest for pattern B. Now, comparing the perceptual complexities of the mosaic and envelope interpretations within each pattern, the suggested segmentation is supported only for pattern B.

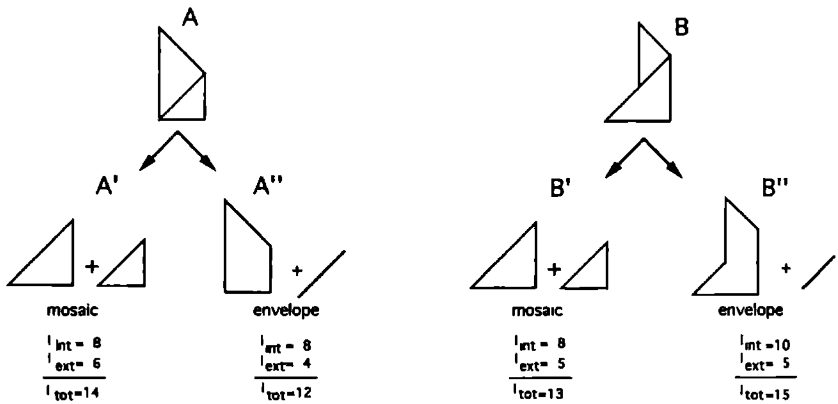


Figure 1. For both pattern A and pattern B, two interpretations (mosaic and envelope) are shown. The segmentation into two triangles (mosaic) seems to be more compelling for pattern B. Apparently, this segmentation is facilitated by its concave angle. Although this concavity is not encoded explicitly (see text), it implicitly affects the perceptual complexities of the possible interpretations.

In order to demonstrate that segmentation at concavities may depend on structural hierarchy as well, consider the concave objects A and B in Figure 2. Object A can be described by means of one superstructure and one subordinate structure as indicated in Figure 2A'. The structural description of object B has two superstructures coupled each with a subordinate structure (see Figure 2B'). Therefore, object A is predicted to be perceived as a unitary shape, whereas object B is predicted to be perceived as a dual shape (cf. Leeuwenberg & Van der Helm, 1991). Because of that, a segmentation at the concavities is expected to be more prevalent for object B.

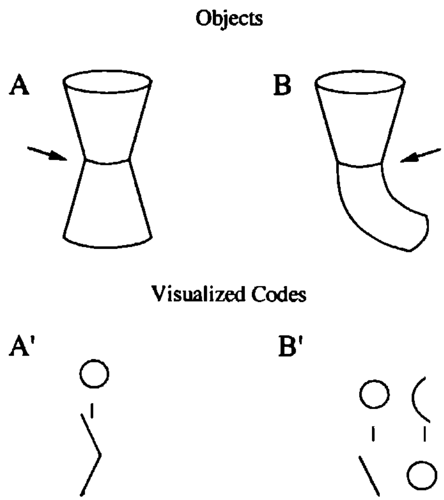


Figure 2. The structural description of object A has only one superstructure, whereas the structural description of object B has two superstructures. According to these SIT descriptions a segmentation at the concavities is more compelling for object B than for object A.

A final remark we want to make in this section on semantics is that contour tracing as, for example, in Figure 1 is not to be taken as an actual process account. This would be a misconception. One of the things that the visual system certainly does not do is sequentially tracing the contours of all shapes in the visual field. The tracing of the contour should rather be considered as a heuristic method, yet a reasonably good one, as the contour of a shape reveals many relevant global and local characteristics of that shape. In addition to the contour codes, other mappings of a pattern on a symbol series have been employed, such as a "centric" mapping starting in the centre of a pattern (Leeuwenberg, 1971). Despite the reasonable success of the above semantic mappings, challenging research in the future would aim at the improvement of the semantic mapping, such that fewer shape characteristics get lost somewhere between pattern and symbol series. One suggestion could be to specify not only the lengths between successive angles on the contour, but also the lengths between all other pairs of angles (see, for a similar proposal, Deutsch, 1955). In this way the regularities induced by the relative position of each element with respect to all other elements could be considered. Further research, however, has to show whether such extensive coding indeed accounts for substantially more of the relevant pattern characteristics.

3 Reinterpreting demonstrations against SIT

Perhaps the most compelling phenomenon that seemed to undermine the SIT assumptions has been the local-effect phenomenon (Kanizsa, 1985). This local-effect phenomenon has been demonstrated for occlusion patterns by several researchers (e.g. Kanizsa, 1985; Rock, 1983; Boselie, 1988; Boselie & Wouterlood, 1989). In those demonstrations global completions seem to be simpler than local completions, yet local completions are preferred to global completions. The integrative model proposed in Chapter 2, however, removes much of the discrepancy between 'local preference' and global simplicity.

In general, the theoretical considerations and experiments in this thesis contribute to the ongoing discussion on the impact of global and local pattern properties. Although the terms "global" and "local" are frequently used in the literature, there is no unique definition of them. Often the concepts global and local refer to metrical proportions. For example, Navon (1977) refers with the term global to the low spatial frequency structure of a pattern. The distinction between global and local can also be made with respect to the span of a certain pattern property. In this way a specific junction type can be considered as a local cue, whereas a bilateral symmetry can be considered as a more global aspect, as it covers a greater part of a pattern. As argued in Chapter 3, our view is that the influence of local cues depends on global characteristics. For example, a T-junction between surfaces is often regarded as a local cue for occlusion, yet the regularities of the shapes may be decisive as to whether an occlusion will be perceived or not (see for example Figure 2, Chapter 2).

The global-local issue can be found at several instances in this thesis. In all chapters, predictions on the interpretations of visual patterns are based on the simplicity of structural descriptions. These predictions concern decompositions of symbol series, amodal completion of surfaces, and the dominance of object components. In Figure 3, from each of the three stimulus domains, an example is presented once more. Below each pattern, two plausible 'solutions' are given. The qualifications "global" and "local" are given on the basis of mere stimulus properties. For pattern A (series) the clustering in A' has the largest component and has been qualified as global, whereas A'' is qualified as local. For pattern B (surfaces) completion B' is qualified as global, as it is the more symmetric one, whereas B'' is qualified as local. For pattern C (objects) the dominance relationship in C' is qualified as global, as it considers the largest contour component as a superstructure, whereas C'' is qualified as local. Note that for each pattern the local 'solution' is preferred, and indeed predicted on the basis of global simplicity according to the argumentations in the previous chapters. So, at an intuitive level there seems to be a discrepancy between local preference and global simplicity; consequently the patterns could be seen as counter examples of SIT. In fact, they are the opposite.

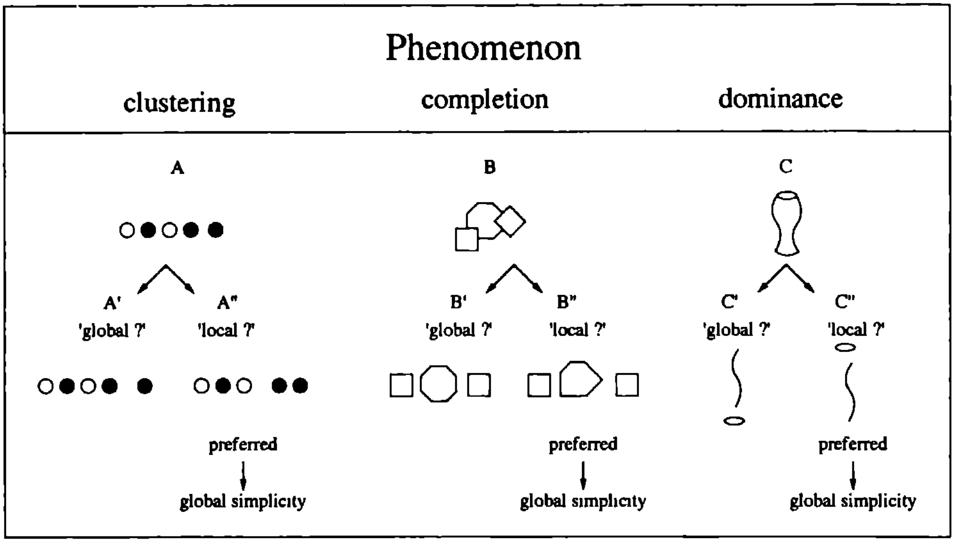


Figure 3. Three illustrations of the congruency between 'local preference' and global simplicity. An example is given of each of the three stimulus domains discussed in this thesis.

The above demonstrations further strengthen our statement that the distinction between global and local is by itself post hoc and that this distinction is not needed to explain the preference of interpretations. Instead of a-priori explanatory concepts the notions "global" and "local" should be considered as a-posteriori assignments.

4 Comparing SIT to alternative approaches

At several instances in this thesis the assumptions and predictions of SIT were compared to those of alternative approaches. We will briefly review some of these approaches and make some additional contrasts which serve as a further orientation of the SIT model. The alternative approaches are clustered in four categories: local-cue approaches, likelihood approaches, process approaches, and transformational approaches. Notice, however, that these approaches are not mutually exclusive as specific theories may share characteristics of more than one of them.

4.1 *Local-cue approaches*

Local-cue approaches assign a decisive role to certain local cues such as a T-junction. The completion models of both Kellman and Shipley (1991) and Wouterlood and Boselie (1992) combine local cues, such as edge orientation or junction type, with the good-continuation principle. In Chapters 2 and 3 we have argued that completion models solely based on local cues cannot hold (see also the previous paragraph).

4.2 *Likelihood approaches*

The likelihood principle, originally formulated by Von Helmholtz (1867/1962), states that the preferred perceptual organization reflects the most likely object or event. As mentioned in the introductory chapter, various contemporary concepts and approaches are related to this general principle, such as the avoidance-of-coincidence principle (Rock, 1983), the general-viewpoint principle (Huffman, 1971), and the concept of nonaccidental properties (Biederman, 1987). Various researchers (Mach, 1886; Goodman, 1972; Sober, 1975; see also Hatfield & Epstein, 1985) have argued that the likelihood principle and the minimum principle could be two sides of the same coin, as in many cases the most likely interpretation is the simplest interpretation and vice versa. We do not agree with this exchangeability of concepts. In Chapter 5, we have implicitly criticized the likelihood principle by means of a rather straightforward calculation of the probability that the projection of a straight line actually stems from a straight line. Considering all possible shapes that may result in a straight line projection, the chance that the actual shape is a straight line appears to be very small. This rather counter-intuitive result shows that a probability calculus which is based on the number of occurrences, cannot provide an explanatory framework for the preference for an interpretation. Leeuwenberg and Boselie (1988) argued that the probability of an interpretation is related to the size of the induced set of a pattern (cf. Garner, 1970; Collard & Buffart, 1983), which in turn is determined by the regularities in the pattern. Therefore the probability of occurrence is not to be regarded as a primary explanatory principle, which in fact reduces the likelihood principle to a secondary concept. In everyday life, however, the probability of occurrence is such a compelling subjective experience that it is often taken as a cause rather than as an effect. Regarding the nonaccidental properties, we do not deny their effects, but, again, we do deny that probability is the appropriate concept for explaining them. Instead, in our view the specification of regularity provides the correct explanation of these effects. However, once regularity is taken as an explanatory framework, the concept of regularity has to be taken to its full extent. This is exactly what is proposed by SIT.

The above considerations have their consequences for models of perception that make use of a-priori defined descriptive components based on nonaccidental properties, such as the RBC approach (Biederman, 1987). The classification task in Chapter 5, and the results of the experiments in Chapter 6 support the SIT assumptions more strongly than the RBC assumptions. This does not mean that SIT provides alternatives to all aspects of RBC. Because of the use of predefined components, RBC provides a bottom-up processing account, which allows a process modelling of object recognition (see also Hummel & Biederman, 1992). In general, likelihood approaches permit, more than the minimum principle, such process accounts of perception.

4.3 *Process approaches*

As stated before, SIT is first of all a representation theory. Within SIT, perceptual organization depends on the simplicity of the representation. According to process approaches the perceptual organization depends on properties of the perceptual process. Leeuwenberg and Van der Helm (1991) compared the SIT approach with several process approaches, such as the global-precedence approach (Navon 1977), the preattentive orientation detection (Beck, 1982), and the RBC approach (Biederman, 1987). They argued that various phenomena that in those approaches are assigned to perceptual precedence effects as conceived in a linear stage model, can very well be explained by postperceptual dominance effects in line with the minimum principle (see for example Kinchla & Wolfe, 1979, and Martin, 1979, for criticism on the global-precedence hypothesis).

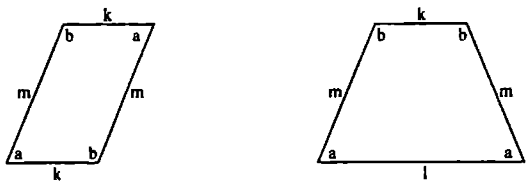
Although we are primarily interested in the outcome of the perceptual process and not in the process itself, the SIT model and the experimental results may yet suggest constraints on processing aspects. For example, in Chapters 2 and 3, we argued that preference data could be explained by just one selection criterion by means of which interpretations are all treated in the same way. On the basis of this conclusion, we are inclined to assume just one generative process that results in competing interpretations. This opposes a recent proposal by Sekuler (1994) who assumed two different processes in pattern completion: a global and a local process, each generating its unique interpretation. In that model, a-priory fixed parameters are suggested to weigh certain properties of the completions. So, whereas the model of Sekuler (1994) expresses a competition between processes generating different completions, the SIT model suggests a competition between interpretations generated by one process.

All our experiments were set up to test the presence of certain interpretations in a relatively late stage of the generation process. Therefore, the SOAs in the priming experiments were set reasonably large (in the order of hundreds of milliseconds). In contrast, Mens and Leeuwenberg (1988) employed very short SOAs (in the order of tens of milliseconds) as their objective was to gain access to the primary perception of structure. In line with Mens (1988) we affirm that such experiments, and their possible agreement with SIT, do not mean to take SIT as a process model. Nevertheless, in the past few years some attempts have been made to elaborate on process aspects. As mentioned, the development of the encoding program PISA (Van der Helm, 1988) takes away some of the criticism regarding possible processing accounts. It has never been claimed, however, that the algorithm is a model for the actual perceptual process. Van Leeuwen, Buffart, and Van der Vegt (1988) have elaborated on processing aspects by means of a network model on the generic relations between different codes. Although their approach does not fit in with the accessibility criterion of the current SIT model, it demonstrates that the idea of a maximal specification of regularity is susceptible to an account in process terms.

4.4 *Transformational approaches*

SIT's basic concepts of holographic regularity and transparent hierarchy provide a unique view on the concept of regularity. Until the development of the concept of accessibility, the transformational approach, based on mathematical Group theory, was the only formalism available to specify kinds of regularity. This mathematical approach has been applied to phenomena of perceptual organization by various researchers (cf. Garner, 1970; Palmer, 1991). By that approach, regularity is assessed by groups of transformations that leave a pattern invariant. Van der Helm and Leeuwenberg (1995) recently argued that SIT's approach and the transformational approach agree on the perceptual structure of repetition, but differ essentially on the perceptual structure of mirror symmetry. Within the transformational approach, mirror symmetry is an all-or-nothing property, as it is represented by means of a 180 degrees 3D rotation on its axis of symmetry. Within SIT, mirror symmetry is a graded property as it is represented in a point-by-point fashion, relating points in the two symmetry halfs. This difference can be related to various phenomena such as noise (in)sensitiveness of regularities in dot patterns: mirror symmetric dot patterns appear to be much less sensitive to noise than twofold repetition dot patterns (see Van der Helm & Leeuwenberg, 1995). In general, the concept of holographic regularity appears to account better for the "goodness" of patterns than does the transformational approach. "Goodness" has been quantified in line with McKay's (1969) "weight of evidence", by considering the amount of support for a pattern regularity, as expressed by the equation "W=E/M", where E is the number of holographic identities that constitute the regularity, and M the total number of elements in the pattern. By means of an illustration we apply the findings of Van der Helm and Leeuwenberg (1995) to line patterns. Consider the parallelogram (A) and the trapezoid (B) in Figure 4. A primitive code of the parallelogram is 'ambkambk', which can be reduced to a simplest code '2*(ambk)', with $I_{internal}$=5. A primitive code of the trapezoid is 'ambkbmal' which can be reduced to a simplest code 'S[(a)(m)(b),(k)]l' with $I_{internal}$=5. Now, although the complexities are the same, there is a difference in support of their regularity or "goodness": the simplest code of the parallelogram contains one holographic identity, between the identical clusters 'ambk'. As the total number of elements is 8, the goodness of the parallelogram is W=1/8. The simplest code of the trapezoid contains three holographic identities, one for each of the three elements 'b', 'l', and 'k'. As the total number of elements is 8 again, the goodness of the trapezoid is W=3/8. So, according to the goodness measure the trapezoid is a "better" shape than the parallelogram. Note that, for every shape with a perfect mirror symmetry, a code can be found for which W=1/2. For the trapezoid this can be achieved by splitting up the line elements 'k' and 'l' each into equal elements 'k*', 'k*', and 'l*', 'l*', respectively. Now the primitive code for the trapezoid would be 'l*ambk*k*bmal*', which results into 'S[(l*)(a)(m)(b)(k*)]', with $I_{internal}$=5 so that W= 5/10. This example demonstrates that the concept of holographic regularity as developed and employed within SIT accounts for differences in perceived goodness. Such differences are not predicted by the transformational approach.

A B



Code: 2* (ambk) Code: S[(a)(m)(b),(k)]l

$I_{int}=5$ $I_{int}=5$

W=1/8 W=3/8

Figure 4. The shapes A and B have an equal perceptual complexity, yet the quantified goodness (W) of shape B is higher than the quantified goodness of shape A. The difference in goodness can be explained by an holographic account of regularity.

5 Testing SIT on a variety of stimulus material

At various instances in this thesis, predictions emerging from the SIT model were tested. These tests comprised the preference for specific organizations of symbol series (Chapter 1), the preference for either mosaic interpretations or completion interpretations of surfaces (Chapter 2), the competition and multiplicity of completion interpretations (Chapters 3 and 4), the classification of object drawings (Chapter 5), and the dominance of superstructures in object drawings (Chapter 6).

As mentioned before, all experiments tested the presence of certain interpretations in a relatively late stage of the perceptual process. In future research, the primed-matching paradigm, employed in Chapters 4 and 6, will certainly be a useful tool in the exploration of various process aspects on the generation of interpretations (cf. Sekuler & Palmer, 1992). Moreover, the priming effect due to representational similarity between prime and test shape also provides an opportunity to test key assumptions about SIT representations. For example, the paradigm may be employed for testing the regularities and hierarchical combinations that are allowed within SIT. Indeed, in recent pilot experiments (Van Lier, 1995) the paradigm has begun to prove its value in assessing specific regularity structures. Because of their potential impact, a brief indication of the experimental setup and results will be given here. Consider Figure 5. P represents a possible prime. T1 and T2 are possible test shapes in the matching and nonmatching test pairs. Note that prime P and test shape T1 have a high physical similarity, whereas prime P and test shape T2 have a high representational similarity as they share the same regularity structure. The procedure was the same as that in Chapters 4 and 6. The prime duration was set at 400 ms. It appeared that there was no facilitating effect of prime P on the matching test pair consisting of shapes T1. There was, however, a facilitating effect on the matching test pair consisting of shapes T2. As there is no physical similarity between prime P and test shape T2, the latter priming effect must be based on the similarity of the regularity structure. The occurrence of this priming effect is indeed promising and might enable us in future research to determine which kind of regularities are picked up, at which moment in the perceptual process. The manipulation of the ISI furthermore provides the opportunity to test the persistence and the decay of regularity structures that have been picked up.

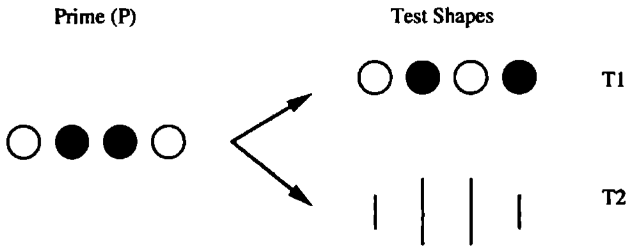


Figure 5. The primed-matching paradigm provides the opportunity to test the representational impact of specific regularity structures. An example of possible primes and test shapes is given here. P and T1 have a high physical similarity, whereas P and T2 have a high representational similarity. In a pilot experiment it appeared that the latter combination evokes higher priming effects.

In future research, experiments of the above kind will provide new opportunities to test fundamental SIT assumptions. At this point, we want to endorse the importance of a continuous interaction between empirics and theory. Theory without experiments may drift away from "perceptual reality", whereas an overemphasis on experiments may cumulate into data bases that can hardly be interpreted within a unifying frame. After all, interpretation of results cannot proceed independently from a theoretical framework. Theoretical concepts guide the experimental setups, whereas experimental data may elicit new theoretical concepts. As long as such new concepts are consistent with the existing framework, they potentially reflect a fully legible improvement which is by no means ad hoc.

6 Concluding remarks

The most fundamental theoretical concept within SIT certainly is the global-minimum principle. This concept allows SIT to model a variety of phenomena in visual perception on a diversity of stimulus material. Indeed, each topic in this thesis can be understood from that single point of view. With that, the concept of simplicity also holds on a metatheoretical level. The still existing 'open ends' of the theory are by no means at odds with the still developing status of the theory. In that light, this thesis may be regarded as an attempt to put into place a few more jigsaw pieces supporting the general notion of simplicity in visual shape.

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Samenvatting

Bij onze visuele waarneming komt heel wat 'kijken'. Toch kost het ons schijnbaar geen enkele moeite om de wereld om ons heen binnen een fractie van een seconde te interpreteren. In deze korte tijd wordt het licht dat op het netvlies van ons oog terechtkomt, vertaald in een veelal begrijpelijke, betekenisvolle omgeving. Het is ronduit verbazingwekkend hoe uit de 'eenvoudige' fysiologische prikkels van gevoelige receptoren in het oog een over het algemeen heldere representatie wordt opgebouwd in onze hersenen. Dit produkt van het waarnemingsproces is zelfs zó overtuigend dat het gemakkelijk wordt verward met het waargenomene zelf. In feite is het niet meer dan een weerspiegeling daarvan. Bedenk bijvoorbeeld dat zowel kleur als vorm behoren tot het produkt van het visuele systeem en als zodanig slechts bestaan voor de waarnemer. Ondanks deze principiële onzekerheid over de externe wereld zijn waarnemers het verrassend vaak eens. Over het algemeen blijkt dat - hoewel elk visueel patroon in principe op vele manieren geïnterpreteerd kan worden - slechts één bepaalde interpretatie de voorkeur heeft. Dit proefschrift heeft als onderwerp het produkt van de waarneming en de dwingende voorkeur voor specifieke interpretaties.

In de historie van het waarnemingsonderzoek is voortdurend gezocht naar organiserende principes: wetmatigheden die vastleggen hoe een willekeurig patroon wordt geïnterpreteerd. Veel van de voorgestelde wetmatigheden bleken al gauw te summier. Voorts kon er geen eenduidige relatieve sterkte van de verschillende wetmatigheden worden aangegeven, waardoor predictie in specifieke gevallen erg moeilijk bleek. Koffka (1935) deed een poging om de verschillende principes te integreren door middel van het concept 'Prägnanz'. Dit hield in dat de waarneming tendeert naar zogenaamde 'goede vormen'. Omdat echter duidelijke specificaties ontbraken konden geen precieze voorspellingen worden gedaan. Een belangrijke stap voorwaarts was de introductie van het globaal-minimumprincipe in de visuele waarneming (Hochberg & McAlister, 1953). Dit principe houdt in dat van een visueel patroon altijd de eenvoudigste interpretatie wordt waargenomen. Het is vervolgens natuurlijk wel zo dat, gegeven dit uitgangspunt, het concept 'eenvoud' een nadere specificatie behoeft. Er zijn vele invullingen van dat concept denkbaar; in dit proefschrift staat de Structurele Informatie Theorie (SIT), die geïnitieerd is door Leeuwenberg (1969, 1971), centraal.

Om te bepalen hoe eenvoudig (of complex) een interpretatie van een visueel patroon is, wordt binnen de SIT gekeken naar de hoeveelheid regelmaat binnen zo'n patroon. Over het algemeen geldt dat meer regelmaat een beschrijving eenvoudiger maakt. Zo kan een symmetrisch patroon veelal eenvoudiger beschreven worden dan een patroon zonder symmetrie. Binnen de SIT wordt een beperkte set van op regelmaat gebaseerde codeerregels gehanteerd, waarmee verschillende interpretaties van een patroon beschreven kunnen worden (Leeuwenberg 1969, Van der Helm & Leeuwenberg, 1991). Vervolgens kan aan de hand van de beschrijving van elk van die interpretaties de complexiteit, uitgedrukt in informatie-eenheden, worden vastgesteld. De eerder genoemde aanname dat ons visuele systeem een voorkeur heeft voor de interpretatie met de eenvoudigste beschrijving, maakt dat de SIT een eenduidig toetsingscriterium biedt. In het verleden is de SIT dan ook op een groot aantal verschijnselen toegepast. Ondanks succesvol en bevestigend onderzoek is de vermeende tendens naar eenvoud in de visuele waarneming beslist niet zonder controversen. Er zijn diverse tegenwerpingen gedaan tegen de SIT, het codeersysteem en het globaal-minimumprincipe. Zo is de selectie van typen regelmaat die in het model zijn opgenomen lange tijd intuïtief geweest en is ook de kwantificatie van eenvoud niet altijd duidelijk geweest. De belangrijkste tegenwerping wordt misschien wel gevormd door het zogenaamde 'lokaal effect fenomeen'. Kanizsa (1985) liet overtuigend zien dat interpretaties vaak bepaald lijken te worden door lokale kenmerken en niet door globale eigenschappen. Het is in belangrijke mate dit soort tegenwerpingen tegen het SIT-model geweest dat aanzet heeft gegeven tot het onderzoek waarvan in dit proefschrift verslag wordt gedaan. In het kader van die kritiek zijn de volgende doelen nagestreefd in dit proefschrift: (*i*) antwoorden op kritiek op de SIT-codeertaal; (*ii*) herinterpreteren van demonstraties die de SIT ondermijnen; (*iii*) vergelijken van de SIT met alternatieve benaderingen; (*iv*) testen van specifieke SIT-voorspellingen met behulp van een variëteit aan stimulusmateriaal. Deze doelen zullen echter niet achtereenvolgens behandeld worden, maar ze komen op diverse plaatsen in het proefschrift aan bod. In de Epiloog van dit proefschrift zullen we hier verder op ingaan. Het proefschrift heeft twee onderverdelingen. De eerste betreft een classificatie op basis van het stimulusdomein waarbinnen specifieke hypothesen getest zijn: Reeksen (deel 1), Oppervlakken (deel 2) en Objecten (deel 3). De tweede indeling is meer fundamenteel van aard en betreft de vier hoofdthema's van dit proefschrift: 'kwantificatie van eenvoud', 'unificatie door eenvoud', 'diversiteit door eenvoud', en 'componenten door eenvoud'. Deze laatste indeling wordt in deze samenvatting verder aangehouden.

Kwantificatie van eenvoud
Binnen de SIT wordt een visueel patroon gerepresenteerd middels een symboolreeks. De symbolen kunnen bijvoorbeeld verwijzen naar opeenvolgende contourdelen en hoeken van het patroon. Vervolgens wordt deze zogenaamde primitieve symboolreeks met behulp van specifieke codeerregels gereduceerd door zoveel mogelijk regelmaat aan de reeks te onttrekken. Onlangs hebben nieuwe theoretische inzichten (Van der Helm, 1988; Van der Helm & Leeuwenberg, 1991) geleid tot een formalisering van het concept regelmaat. De formalisering komt, op zijn minst voor een deel, tegemoet aan eerder geuite kritiek op het codeersysteem. Uitgangspunt is het zogenaamde accessibiliteits-criterium, dat stelt dat perceptueel relevante codeerregels gekenmerkt worden door zogenaamde holografische regelmaat en transparante hiërarchie. In Hoofdstuk 1 zullen we deze concepten uitgebreid toelichten. Slechts een klein aantal regelmatigheden voldoet aan deze eigenschappen en alleen deze worden dan ook toegepast in het SIT-codeersysteem, te weten 'Iteratie', 'Symmetrie' en 'Alternatie'.

De complexiteit van een code wordt uitgedrukt in termen van informatie-eenheden. In het verleden zijn diverse kwantificaties overwogen die complexiteit van een code bepalen. In Hoofdstuk 1 zullen we met de term 'I_{old}' refereren naar de informatiemaat die in het verleden het meest werd gebruikt. Aan deze oude informatiemaat kleven een aantal conceptuele bezwaren. Zoals we onder meer zullen toelichten is een belangrijk bezwaar van deze maat dat incompatibele code-eenheden bijdragen aan 'I_{old}'. Voorts is deze informatiemaat bedoeld als indicatie voor de hoeveelheid 'opslagruimte' die nodig is om de code in het geheugen te bewaren. In Hoofdstuk 1 zullen we daarentegen het standpunt verdedigen dat de complexiteit van een code niet zozeer bepaald dient te worden aan de hand van de vereiste geheugenruimte maar veeleer aan de hand van de semantische inhoud van die code (d.w.z. de beschrijving van regelmaat). De nieuwe informatiemaat (I_{new}) die in Hoofdstuk 1 wordt geïntroduceerd komt hieraan tegemoet. Ook blijkt deze maat het perceptuele verschil tussen Herhaling en Symmetrie beter te verdisconteren. In een experiment worden de informatiematen I_{old}, I_{new}, alsmede een aantal alternatieve maten, getoetst op seriële patronen. In de experimentele opzet is gekozen voor seriële patronen omdat deze het dichtst bij de primitieve symboolreeks staan. Gedurende het experiment kregen proefpersonen telkens eerst een symboolreeks op een monitor te zien. Daarna werden twee mogelijke organisaties van deze reeks afgebeeld, door middel van een clustering van symbolen. Deze clustering weerspiegelde een bepaalde codering van de symboolreeks. De proefpersonen dienden vervolgens aan te geven aan welke clustering zij de voorkeur gaven. Het blijkt dat oordelen van de proefpersonen verreweg het beste kunnen worden voorspeld met behulp van de nieuwe informatiemaat.

Unificatie door eenvoud

In dit thema zullen we ons bezighouden met de semantiek van het codeersysteem, dit in tegenstelling tot het vorige thema dat refereerde aan de syntaxis van het codeersysteem. Bij de semantiek staat de vraag centraal op welke patroonaspecten het concept 'eenvoud' betrekking heeft. We zullen ons toeleggen op lijnpatronen die doorgaans geïnterpreteerd worden als een mozaïek van naast elkaar liggende vlakken, of als een compositie van achter elkaar liggende vlakken waarbij een der vlakken gedeeltelijk aan het oog is onttrokken. In het laatste geval lijkt het gedeeltelijk geoccludeerde vlak door het perceptuele systeen te worden aangevuld, hetgeen ook wel completie wordt genoemd. Dit stimulusdomein is interessant omdat in het recente verleden juist op dit gebied de meeste tegenvoorbeelden van de tendens naar globale eenvoud zijn gevonden (Kanizsa, 1985; Rock, 1983, Boselie, 1988; Boselie & Wouterlood, 1989).

In Hoofdstuk 2 zullen we beargumenteren waarom niet alleen de eenvoud van de vlakken zélf beschouwd moet worden, maar ook de relatie tussen de vlakken en het patroon. We maken daarbij een onderscheid tussen de zogenaamde geheugencomplexiteit en de perceptuele complexiteit. In het verleden is bij de predictie van patrooninterpretaties voornamelijk de geheugencomplexiteit gehanteerd. Daarbij werd de oude informatiemaat toegepast (zie bijvoorbeeld Buffart, 1983; Boselie 1988). De perceptuele complexiteit gaat uit van drie aspecten die gezamenlijk de complexiteit van een interpretatie bepalen, namelijk vorm, positie en occlusie. In het voorgestelde model zijn deze drie aspecten ingebed in drie verschillende structuren, respectievelijk de interne, de externe en de virtuele structuur. Omdat regelmaat tussen patroonelementen een bindend effect heeft op die elementen, zullen regelmatigheden binnen de interne structuur de betreffende interpretatie ondersteunen, terwijl regelmatigheden in de externe structuur die interpretatie juist afzwakken. De virtuele structuur betreft die elementen die niet aanwezig zijn in de distale stimulus, maar wel in de interpretatie van die stimulus. De complexiteit van elk van de drie structuren kan worden uitgedrukt in termen van structurele informatie. We veronderstellen dat de som van de drie complexiteiten de totale perceptuele complexiteit van een interpretatie bepaalt en dat deze totale perceptuele complexiteit van de geprefereerde interpretatie lager is dan die van elke andere interpretatie. In Hoofdstuk 2 wordt dit voorstel getest op een groot aantal kritische patronen en data uit drie publikaties: Buffart, Leeuwenberg en Restle (1981), Boselie (1988) en Boselie en Wouterlood (1989). Het eerste artikel is geselecteerd omdat daarin de toepasbaarheid van de SIT op het occlusie- en completiefenomeen wordt geclaimd. De laatste twee artikelen zijn juist geselecteerd omdat zij een groot aantal vermeende tegenvoorbeelden van het eenvoudsconcept bevatten. Uit de analyse blijkt ondermeer dat voor 95% van alle patronen de meest geprefereerde interpretatie goed voorspeld wordt door de totale perceptuele complexiteit. $I_{internal}$, $I_{external}$, en $I_{virtual}$ corresponderen tot op zekere hoogte met bekende perceptuele tendensen, respectievelijk 'goedheid van vorm', het 'vermijden van coïncidentie' en het principe van 'goede voortzetting'. Deze drie tendensen worden in het besproken model geünificeerd met behulp van het eenvoudsconcept.

Diversiteit door eenvoud
In overeenstemming met het globaal-minimumprincipe veronderstellen we dat het perceptuele systeem van elk visueel patroon meer dan een interpretatie genereert. Herbart (1850) suggereerde al dat de sterkte van een interpretatie afhankelijk is van de aantrekkelijkheid van alternatieve interpretaties. Door middel van een aantal experimenten is een antwoord gezocht op de vraag of het visuele systeem inderdaad verscheidene met elkaar rivaliserende interpretaties genereert. We hebben ons daarbij beperkt tot het domein van occlusiepatronen en twee verschillende completie-tendensen. De eerste tendens resulteert in de eenvoudigste vorm, onafhankelijk van de complexiteit van de completie zelf (globale completie). De tweede tendens resulteert in vormen waarbij de completie zelf zo eenvoudig mogelijk is, maar waarbij de uiteindelijke vorm niet de eenvoudigste hoeft te zijn (lokale completie).

In Hoofdstuk 3 zijn twee experimentele paradigma's toegepast op occlusiepatronen. Voor alle patronen waren zowel globale als lokale completies mogelijk. In het eerste experiment werd aan proefpersonen gevraagd of ze hun spontane interpretatie van occlusiepatronen wilden aangeven (zie ook Buffart, Leeuwenberg, & Restle, 1981; Boselie, 1988; en Boselie & Wouterlood, 1989). De resultaten illustreren duidelijk de relevantie van beide typen completies. Het tweede paradigma betrof de zogenaamde 'simultaneous matching'-taak, gedeeltelijk overgenomen van Gerbino en Salmaso (1987). Hierbij kregen proefpersonen gelijktijdig een samengesteld patroon en een andere figuur op een monitor te zien. De proefpersonen dienden daarbij zo snel mogelijk aan te geven of de laatste figuur in het samengesteld patroon aanwezig kon zijn. Uit dit experiment blijkt dat het 'matchen' van een figuur met een gedeeltelijk geoccludeerde figuur hogere response-tijden oplevert dan het matchen van die figuur met een patroon waarin die figuur niet geoccludeerd is. Dit in tegenstelling tot de resultaten van Gerbino en Salmaso. Deze auteurs gebruikten echter occlusie-patronen waarbij de globale completie niet verschilde van de lokale completie. De spontane voorkeur voor bepaalde interpretaties (experiment 1) blijkt voorts significant te correleren met de resultaten op de matching taak (experiment 2). Al deze gegevens ondersteunen het idee dat de voorkeur voor een bepaalde completie het resultaat is van een competitie tussen interpretaties. In Hoofdstuk 3 wordt verder nagegaan aan de hand van welke factoren de relatieve preferenties voorspeld kunnen worden.

In Hoofdstuk 4 wordt gezocht naar verdere evidentie voor de generatie van meerdere completies. Dit keer met behulp van het zogenaamde 'primed-matching' paradigma (Beller, 1971). Dit paradigma is door Sekuler en Palmer (1992) voor het eerst op occlusiepatronen toegepast. In een typische experimentele setting zien proefpersonen eerst gedurende enige tijd (tussen 50 ms en 1000 ms) een patroon, de zogenaamde prime, op een monitor. Zo'n prime kan bijvoorbeeld een occlusiepatroon zijn. Daarna verschijnt een testpaar op de monitor. Dit testpaar bestaat uit twee al dan niet identieke figuren. De taak van de proefpersonen is telkens zo snel mogelijk vast te stellen of de twee figuren van het testpaar wel of niet gelijk zijn aan elkaar. Uit eerdere experimenten (Sekuler en Palmer, 1992) is gebleken dat indien de figuren identiek zijn (matching-conditie) én indien de figuur aanwezig is in de prime - al dan niet geoccludeerd - de prime een faciliterende werking heeft op de snelheid van de response op het testpaar. Dit paradigma is een bruikbaar instrument om de actuele representatie van proefpersonen te testen omdat de response-snelheid sterk afhankelijk blijkt te zijn van een eventuele representationele overeenkomst tussen prime en testpaar. In de experimenten van Hoofdstuk 4 zijn de prime-effecten op globale, lokale en zogenaamde anomale completies onderzocht. Voorts worden twee mogelijke definities van het prime-effect ten gevolge van de occlusie-prime beschouwd. De occlusie-primes bestonden uit occlusie-patronen waarbij de globale completie domineert. Het blijkt dat voor deze set patronen het prime-effect voor de globale completies inderdaad het grootst is. Voorts zijn de prime-effecten op de anomale completies over het algemeen het laagst, terwijl de effecten op de lokale completie veelal een tussenliggende positie innemen. We concluderen dat naast de globale completie ook de lokale completie gegenereerd wordt. Een tweede experiment is uitgevoerd ter controle op de mogelijkheid dat het prime-effect zich 'verbreidt' van de globale completie naar de lokale completie. Dit keer zijn veel meer completies tussen de globale en de lokale variant getest. De resultaten van dit experiment bevestigen de speciale status van globale en lokale completies.

Componenten door eenvoud

We zullen nu het debat tussen het globaal-minimumprincipe en het waarschijnlijkheids-principe ter hand nemen. De discussie zal zich daarbij toespitsen op de aard van objectrepresentaties. Een belangrijk aspect van SIT's objectrepresentaties is dat de descriptieve componenten van een representatie niet vooraf gegeven zijn, maar afhankelijk zijn van de eenvoudigste representatie. Dit in tegenstelling tot modellen waarbij de waarschijnlijkheid van een gebeurtenis centraal staat. Een vooraanstaand model op dit gebied is het Recognition By Components (RBC) model van Biederman (1987). RBC definieert descriptieve componenten a priori aan de hand van zogenaamde 'nonaccidental properties' (NAPs).

In Hoofdstuk 5 worden allereerst objectclassificaties van SIT en RBC met elkaar vergeleken. In deze vergelijking staat de as van een object centraal. Binnen het RBC-model wordt de keuze van de as van een object bepaald door zowel structurele als metrische criteria. In onze visie leidt een dergelijke specificatie van assen al snel tot ambiguïteit en onduidelijkheid. In Hoofdstuk 5 zullen we laten zien dat, hoe meer de keuze van de as wordt geleid door structurele constantie, hoe meer deze in overeenstemming is met de uitgangspunten van SIT. Bovendien wordt de perceptuele classificatie van objecten bij een hoge graad van overeenstemming beter voorspeld. In Hoofdstuk 5 tonen we verder aan dat de waarschijnlijkheid van een niet-accidentele eigenschap niet in overeenstemming is met de zogenaamde Bayesiaanse waarschijnlijkheidsrekening. We concluderen dat de vermeende waarschijnlijkheid feitelijk gebaseerd is op classificaties ten gevolge van regelmatigheden. Ter verklaring van dergelijke classificaties dienen daarom juist deze regelmatigheden als uitgangspunt genomen te worden, hetgeen in overeenstemming is met de SIT-uitgangspunten en het globaal-minimumprincipe.

Een andere belangrijke eigenschap van SIT's representaties is de hiërarchische relatie tussen de descriptieve componenten. Binnen zo'n hiërarchische beschrijving wordt het hoogste niveau ook wel de superstructuur van een object genoemd. De lagere niveaus worden de subordinate structuren genoemd. In overeenstemming met Leeuwenberg en Van der Helm (1991) veronderstellen we dat de superstructuur perceptueel dominanter is dan de subordinate structuur. Dit laatste wordt ook wel de superstructuur-dominantie-hypothese genoemd.

In Hoofdstuk 6 zullen we bovenstaande hypothese testen met behulp van het al eerder genoemde 'primed-matching' paradigma (Hoofdstuk 4). Twee experimenten worden besproken. In het eerste experiment zijn de testfiguren opgebouwd uit lijntekeningen van objecten. De primes bestonden uit bepaalde vlakken van deze objecten en correspondeerden ofwel met de superstructuur ofwel met de subordinate structuur. Er waren twee priming condities: de feitelijke en de frontale conditie. In de feitelijke conditie had de prime exact dezelfde vorm als het corresponderende vlak in de tekening van het object. In de frontale conditie werd dit vlak afgebeeld zoals het er in het frontaal-parallelle vlak uit zou zien. Een overeenkomst tussen prime en de superstructuur van de objecten in het testpaar blijkt het matchen van identieke objecten in het testpaar in hogere mate te faciliteren dan een overeenkomst tussen de prime en de subordinate structuur van die objecten. Dit verschil in priming effect is zelfs het grootst voor de frontale primes. Hieruit blijkt dat de representationele overeenkomst tussen prime en componenten in het testpaar een grote rol speelt. In het tweede experiment is onderzocht of de verschillen in priming effect toegeschreven kunnen worden aan de manier waarop de primes ingebed zijn in de objecten. Evenals in het eerste experiment zijn er ook nu faciliterende effecten voor zowel de superstructuur als de subordinate structuur. Er blijken dit keer echter geen verschillen te zijn in de effecten tussen de superstructuur en de subordinate structuur. We concluderen dat deze resultaten de superstructuur-dominantie-hypothese ondersteunen en daarmee de hypothese van een hiërarchische decompositie van objecten, een decompositie die is gebaseerd op het concept 'eenvoud' in visuele vormen.

Curriculum Vitae

Robert Jan van Lier werd geboren in Reuver op 11 juli 1960. Na een onbekommerde jeugd en het 'en passant' doorlopen van achtereenvolgens kleuter-, basis-, en middelbaar onderwijs studeerde hij van 1978 tot 1983 Natuurkunde en Wiskunde aan de Nieuwe Leraren Opleiding (NLO) te Tilburg. Zijn interesse in de perceptieleer werd door een gelijknamig vak tijdens deze studie gewekt. Na een korte stage aan het Instituut voor Perceptie Onderzoek (IPO) te Eindhoven en het behalen van het lerarendiploma wenste hij zijn scholing nog een extra dimensie te geven. Gezien de gerezen belangstelling voor de 'waarnemende mens' begon hij aan de studie Psychologie aan de Katholieke Universiteit Nijmegen (KUN). De stage van die studie volbracht hij op de afdeling Perceptie van het Nijmeegs Instituut voor Cognitie en Informatie (NICI). Naast de gebruikelijke studiewerkzaamheden bekleedde hij voorts verscheidene studentassistentschappen, variërend van het begeleiden van studentenpractica in de persoonlijkheidsleer, de methodenleer en de functieleer tot het schrijven van computerprogrammatuur. Na in 1989 het doctoraalexamen Psychologie met als afstudeerrichting Functieleer 'met genoegen' te hebben behaald en na een verblijf van enkele maanden aan de Universiteit van Triëst met een Erasmusbeurs, begon hij in mei 1990 als Onderzoeker In Opleiding op het door NWO gefinancierde project "Integratie van globale en lokale aspecten van de patroonwaarneming". De projectwerkzaamheden vonden plaats aan het reeds genoemde NICI. In aansluiting daarop was hij van november 1994 tot oktober 1995 als junior onderzoeker verbonden aan hetzelfde instituut. Gedurende beide aanstellingen stonden zijn activiteiten in het teken van de visuele eenvoud. Het boekje dat u nu helemaal uit hebt is daarvan het tastbare resultaat ;-)

Stellingen behorende bij het proefschrift
"Simplicity of visual shape: a structural information approach"

1) Dominantie van globale of lokale patroonaspecten in de waarneming kan alleen begrepen worden vanuit hun gezamenlijke invloed op het totale percept (dit proefschrift).

2) Regelmaat bindt. Dit impliceert dat de perceptuele opdeling van een visueel patroon wordt versterkt door regelmaat binnen de delen, maar wordt verzwakt door regelmaat tussen de delen (dit proefschrift).

3) Het object zoals waargenomen is slechts een tastbare illusie.

4) Perceptie-onderzoek zou niet zo zeer moeten uitgaan van kenmerken van objecten, als wel van de kenmerken van het visuele systeem die de distale stimulus perceptueel tot een object maken.

5) Perceptuele hiërarchie is evenals sociaal-maatschappelijke hiërarchie voornamelijk een interne aangelegenheid.

6) Indien wetenschapsbeoefening en haar directe maatschappelijke relevantie niet meer op gespannen voet staan, dient de waarde van de eerste in twijfel te worden getrokken.

7) Voordat de politiek overgaat tot het invoeren van volksreferenda zou zij zich goed moeten realiseren dat de som van de individuele belangen veelal niet gelijk is aan het gemeenschappelijk belang van de individuen.

8) De hersenen verdienen een betere metafoor dan ze zelf kunnen bedenken.

9) Onsterfelijkheid zou het verlangen naar de dood in grotere mate doen toenemen dan verwacht mag worden op basis van de bijdrage die de sterfelijkheid levert aan het plezier in het leven.

10) AIO's en OIO's worden bij voorkeur weggepromoveerd.

11) Een aantrekkelijke theorie is altijd een beetje onwaarschijnlijk.

12) SIT is een beetje onwaarschijnlijk.

Rob van Lier,
Nijmegen, 23 januari 1996.

NICI
P.O. Box 9104
6500 HE Nijmegen
The Netherlands